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Future energy systems to cope with climate and energy challenges

OECD countries

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Future low carbon energy systems

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Edited by Hans Larsen and Leif Sønderberg Petersen

Risø DTU
National Laboratory for Sustainable Energy

Risø Energy Report 7
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Preface

This Risø Energy Report, the seventh of a series that began in 2002, takes as its point of reference the recommendations of the Intergovernmental Panel on Climate Change (IPCC) in 2007. The IPCC states that if anticipated climate change is to remain in the order of 2 to 3 degrees centigrades over the next century, the world's CO_2 emissions would have to peak within the next 10 – 15 years and ultimately be reduced to approximately 50% of their present level by the middle of the century.

The IPCC states further that this would be possible, provided that serious action is taken now. The different regions and countries of the world are in various states of development, and hence have different starting points for contributing to these reductions in CO_2 emissions.

This report presents state-of-the-art and development perspectives for energy supply technologies, new energy systems, end-use energy efficiency improvements and new policy measures. It also includes estimates of the CO_2 reduction potentials for different technologies. The technologies are characterized with regard to their ability to contribute either to ensuring a peak in CO_2 emissions within 10 – 15 years, or to long-term CO_2 reductions.

The report outlines the current and likely future composition of energy systems in Denmark, and examines three groups of countries: i) Europe and the other OECD member nations; ii) large and rapidly growing developing economies, notably India and China; iii) typical least developed countries, such as many African nations. The report emphasises how future energy developments and systems might be composed in these three country groupings, and to what extent the different technologies might contribute.

The report addresses the need for research and demonstration together with market incentives, and policy measures with focus on initiatives that can promote the development towards CO_2 reductions. Specifically, the report identifies system options and technology mixes that can lead to the emissions peak in 2020 and 50% reduction in the long run, at the Danish and global level.

The report is based on the latest research results from Risø DTU, together with available international literature and reports.

Hans Larsen and Leif Sønderberg Petersen

Risø National Laboratory for Sustainable Energy,
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Summary and recommendations

The global energy scene is currently dominated by two overriding concerns that strongly affect decisions on energy development priorities:

1. Security of supply
2. Climate change

This is especially true for industrialised countries and the more rapidly developing economies. At the same time, many developing countries face really basic energy development constraints that give a quite different meaning to the concept of energy security.

Climate change is widely recognised as the major environmental problem facing the world. The IPCC Fourth Assessment Report states clearly that it is no longer relevant to discuss whether the climate is changing.

Many countries concerned about energy security and climate change have set ambitious targets for renewable energy. Renewable energy worldwide is still dominated by the "old" renewables: hydropower and traditional biomass that supply respectively 6% and 9% of global primary energy demand. Only around 2% of the world's primary energy is currently provided by "new" renewable sources such as wind, photovoltaics and mini- and micro-hydro.

The introduction of more renewables needs to be managed in a way that ensures security of supply and economic performance, while delivering better environmental performance, especially with regard to CO_2 emissions, and less dependence on fossil fuels.

Different solutions for different regions

The countries of the ***OECD*** strongly influence the development of energy demand and new energy supply opportunities. The OECD countries are amongst the fastest in developing new renewable technologies, but they are at the same time becoming increasingly dependent on imported fossil fuels.

OECD countries' growth in energy demand will be much lower than in the rest of the world. The OECD's share of world primary energy is as a consequence expected to decline from almost 49% in 2005 to 34% in 2050, provided that energy and environmental concerns receive the political attention they deserve.

Fossil fuels are currently the dominating energy supply in OECD-countries. Worldwide, the International Energy Agency (IEA) estimates the share of fossil fuels to be approximately 50% in 2050.

Rapidly-developing countries like China and India are important in shaping world trends in economic and energy development and how they develop will affect the possibilities for solving the climate problem. With their enormous new investments in energy infrastructure over the coming decades, these countries have a rare window of opportunity to move towards low-carbon development and low-cost greenhouse gas (GHG) emissions reduction.

With their large territories and population bases, high economic growth and rising living standards, China and India are seeing strong growth in freight and passenger transport. They are already home to several of the world's mega-cities, while new cities are being created and others continue to expand as a result of ongoing massive urbanisation. In view of the lack of oil reserves in these countries, clean vehicles and public transport will be the key technologies for tackling the four-fold challenge of oil supply, local air pollution, traffic congestion and GHG emissions.

These countries generally use energy less efficiently than the OECD countries. China's energy conversion and utilisation efficiency, for instance, is around 25% lower than in industrialised countries. In 2000, energy consumption per physical unit of industrial production in China was around 40% higher than that in advanced developed countries.

Compared to other parts of the world, the rate of economic development in the ***least developed regions*** like ***sub-Saharan Africa*** has been extremely low over the last 45 years.

Climate change is not in itself a priority driver in the energy policies of the least developed countries, since per-capita energy consumption and CO_2 emissions are low. However, in many of these countries the first option for new energy supply is fossil fuel, and there will thus be increasing opportunities for cooperation with industrialised countries. These opportunities include carbon financing and investment in low-emission energy technologies, including clean coal, gas, biomass and other renewables, where appropriate.

Future energy development in the least developed countries will depend strongly on economic growth. This in itself will rely on, among other things, the establishment of an enabling environment in terms of energy infrastructure.

Large-scale infrastructure investments need to go hand in hand with the development of decentralised energy systems at the community level. In the first few years these are expected to be based on small-scale diesel systems, but from 2010 to 2020 they will increasingly be established as hybrid systems based on small-scale hydro, wind or photovoltaics (PV), depending on available resources of wind and hydro.

For these systems, diesel may increasingly be substituted with biofuels, provided that biofuels are not conflicting with food production.

Regional trends and development potential

Although climate change is a common global challenge, the different regions of the world have quite different economic, technological and political preconditions for emissions reduction strategies.

The EU has taken the global political lead with its ambitious targets for GHG reductions and an increased proportion of renewable energy.

The USA has focused much more on domestic energy security; its rapid increase in corn-based bioethanol is a clear example of policy that addresses energy security but contributes very little to GHG reductions or longer-term supply stability.

China and India share a diversified approach that reflects their rapidly-growing economies and associated expansion in energy demand. This includes ambitious targets for renewable energy and energy efficiency, increased domestic production, and collaboration with a large and diverse group of oil- and gas-producing countries, notably in Africa.

While the impacts of climate change will be felt in every region of the world, it is clear that ***poorer developing countries and tropical islands*** are particularly vulnerable. With weak institutions and limited human and financial resources, such countries have limited ability to cope with or adapt to climate change, and they will require strong international support.

The focus on climate and energy security has reduced the political attention given by most potential donors to energy access in the ***poorest countries***.

Finding a global energy development path that addresses both security of supply and climate change is a major challenge that requires coordinated action from all countries.

CO_2 reduction strategies in Denmark

Denmark has the potential for large CO_2 reductions at low additional cost. This will require a mix of measures covering both energy demand and energy supply, the most important of which are:

- Energy savings with annual reductions of 1–3% in energy consumption
- More efficient conventional vehicles and plug-in hybrid vehicles
- Increasing the share of wind power, in particular offshore
- Increased use of biomass for building heating and process heat in industry and CHP plants
- Development of second-generation biofuel technology for transport
- Energy infrastructure development, including flexibility
- New and improved market measures

Global CO_2 reduction possibilities

In the shorter term (up to 2030), the main contributors to GHG mitigation are demand-side measures, efficiency improvements in the energy sector, and reductions in emissions of GHGs other than CO_2. Many short-term energy efficiency measures even have negative abatement costs.

In the longer term, efficiency can be improved in many ways. The multitude of options creates many opportunities for GHG reduction, as well as challenges in identifying the winning technologies.

Climate change is a long-term problem, and early action is important if we are to remain on a lower emissions trajectory that will allow flexibility in the future. Technologies that are important for short-term mitigation are not necessarily sufficient for the long term. A diversified portfolio of choices is needed, and this will require R&D investment over long periods before we reach the ultimate objective.

Recommendations

Denmark could profit by being in the front with developing a low carbon energy system that could increase independence in relation to energy supply and give a competitive advantage in new energy technologies.

There is a need to reinforce Denmark's ***power transmission grid***, in part to meet the needs of future ***offshore wind power*** plants. Electricity storage is an important element in reinforcing the grid. Another pressing matter is the establishment of an ***intelligent grid*** with two-way communication to facilitate the integration of more wind power.

Large-scale integration of renewable energy in Europe requires a ***pan-European transmission network*** to allow effective cross-border power trading and provide mutual support for security and quality of supply.

International collaboration and support for the introduction of new, more efficient, energy technologies for countries like ***China and India*** will be important.

It is important to expand the use of instruments like the ***Clean Development Mechanism*** (CDM) to further the development and implementation of low-carbon energy systems in developing countries.

Stimulating cooperation between existing ***regional power pools in developing countries*** will be essential in exploiting large but regionally-diverse resources such as hydro, coal and natural gas, needed to provide electricity to meet increasing urban demand. ***Rural electrification*** will depend on options for affordable grid based electricity.

Intensified ***research and demonstration*** for new energy technologies, particularly systems adapted to the specific needs of different regions of the world, and preferably in international collaboration, must be stimulated locally, regionally and globally.

Educating the next generation of ***energy specialists, engineers and energy policy makers*** worldwide is important to the development and use of new energy technologies at local, regional and global levels.

Initiatives are needed to raise ***industrial energy efficiency*** at local, regional and global levels.

The global ***building sector*** offers tremendous possibilities for saving energy, but incentives are needed to make this a reality.

Carbon capture and storage (CCS) could be an important medium-term option, allowing the world's large remaining reserves of fossil fuels to be used in an environmentally-benign manner. R&D and international cooperation in CCS should therefore be stimulated.

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Danish and global climate and energy challenges

John M. Christensen, Risø National Laboratory for Sustainable Energy; Prof. Ogunlade Davidson, University of Sierra Leone & Co-chair IPCC WG III

3.1 Major global challenges for energy development

The global energy scene is currently dominated by two overriding concerns that are strongly affecting decisions about energy development priorities:

- Climate change
- Energy security

This is especially true for industrialized countries and the more rapidly developing economies while many developing countries are facing really basic energy development constraints giving quite a different meaning to the concept of energy security. There is broad global recognition of the need to support these countries in their efforts to increase access to cleaner and more efficient forms of energy for the more than 1,6 billion people currently having no access to electricity and largely relying on traditional forms of biomass for basic energy services, but progress is slow in many regions.

The three areas, security, climate and poverty are in several ways interlinked, and ideally national energy policies and development programmes should address all the above issues — or at least not have negative effects in any area. In practice, however, many national policy landscapes have been dominated by just one of these factors. In the political debate the access issue is often seen as a potential climate problem, but most studies indicate that access to basic energy services for the poorest one billion people, even based on fossil resources, will make very marginal contributions to global GHG emissions. The more relevant and pressing political concern is how to limit global emissions and allow the emerging economies to continue their economic growth, but as discussed in this report the technological options will be available and solutions depend on political will and agreements on sharing the technologies and financial resources.

3.2 Climate change – emerging political consensus on the need for urgent action

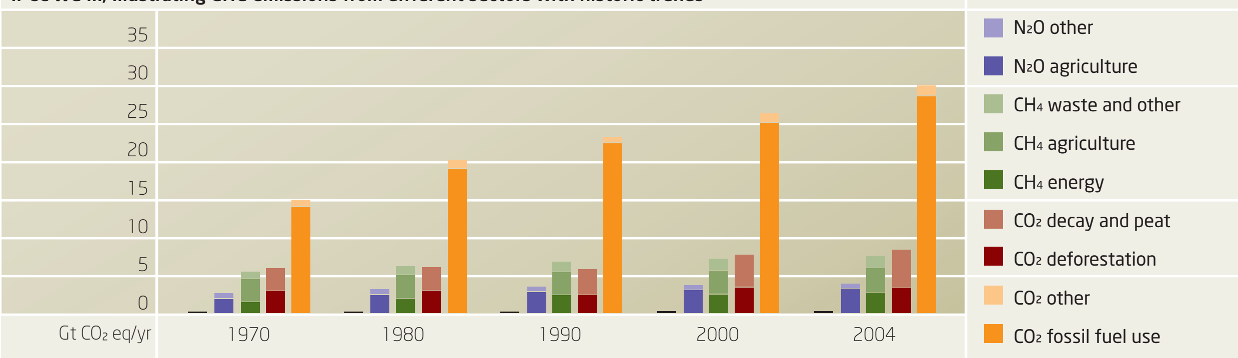
Climate change is widely recognized as the major environmental problem facing the globe and evidence is building that impacts are already being felt in the form of melting icecaps in the polar areas and increased variability of temperature, rainfall and storms in virtually all regions and increasing intensity and frequency of climate extremes.

The scientific consensus underpinning the rising political and public recognition of the climate problem is captured in the recent reports from the Intergovernmental Panel on Climate Change (IPCC). The IPCC Fourth Assessment Report (AR4) clearly states that it is no longer relevant to discuss whether the climate is changing but how much change we are committed to and how fast this will happen and what areas will be affected [1].

The IPCC concludes that in order for the changes to be manageable and avoid acceleration effects the level of GHG concentrations should be contained between 450 to 600 ppm and preferably at the lower end of this range. This is a major challenge since the level is already over 390 ppm and increasing by 10 ppm annually.

It is evident from the AR 4 Working Group III report that if the ambition is to limit the future stabilization level of atmospheric concentrations to less than 600 ppm, this will require unprecedented action in terms of changing the way

Figure 1
IPCC WG III, Illustrating GHG emissions from different sectors with historic trends



especially energy is produced and consumed and strong action on forestry and ecosystems management [2]. Historical emission developments in these sectors are shown in Fig 1.

The IPCC states that the required action is possible with strong policies, technology development and transfer using a broad range of both policy and technology options. The total costs will be significant, but compared with the size of the world economy and its expected growth over the next decades, the cost of the necessary mitigation efforts will only amount to a small fraction of that stipulated growth and therefore in no visible way affect overall economic development patterns. The report, however, underlines that this statement is only true if action is taken urgently as the costs will increase with delayed action.

The timing and cost of reducing GHG emission reductions are, though speculative, fairly well documented, but evidently depend heavily on policy implementation and anticipated technology development.

Table 1
IPCC WG III, Macro-economic costs in 2050 for different stabilization levels

Trajectories towards stabilization levels (ppm CO_2-eq)	Median GDP reduction (%)	Range of GDP reduction (%)	Reduction of average annual GDP growth rates (percentage points)
590-710	0.5	-1 – 2	< 0.05
535-590	1.3	Slightly negative -4	< 0.1
445-535	Not available	< 5.5	< 0.12

The cost of inaction or - in other words - the cost of a more rapidly changing climate has not been assessed in detail by the IPCC. With the nature of the climate problem being truly global where there is no correlation between a country's emissions and its potential impacts from climatic changes. This is not really a question to be answered at the national level. It does, however, come up at the global level when the major GHG emitters discuss future limitations.

While climate change impacts will be felt in all regions of the world it is clear that poorer developing countries and island states in the tropical regions are particularly vulnerable; with weak institutions and limited human and financial resources their ability to cope or adapt is limited and will require strong international support.

One major recent study that has addressed this issue is the Stern Review report: The Economics of Climate Change [3] undertaken with support from the UK Government, which has been widely recognized as a major contribution to especially the international political debate. It should be noted that this report is a national effort and not governed by the intergovernmental rules that apply to the IPCC and their review procedures; but this also means that more direct political statements and suggestions can be made. While some of the specific numbers in the Stern Review have been debated the overall conclusions are quite robust:

"The basic conclusion of the Stern Review is that the costs of strong and urgent action to avoid serious impacts from climate change are substantially less than the damages thereby avoided. This conclusion is robust to a wide range of assumptions "

"Using the results from formal economic models, the Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year." The IPCC GDP estimates for different stabilization levels are shown for comparison in Table 1.

The understanding is, however, only slowly being reflected in political action, in part because public understanding of the required level of change is still limited.

3.2.1 Energy security

The concept of "energy security" is in most political applications very directly linked with energy supply. Securing stable supply is a major political concern and a challenge facing both developed and developing economies since prolonged disruptions would create serious economic and basic functionality problems for most societies.

On a more detailed level the issue of supply security can be disaggregated into a number of more detailed concerns:

- Changes in global distribution of demand and supply
- Increasing import of fossil resources in most OECD countries but also for example for China and India
- Political focus on national control of supply and production
- Affordability of energy imports for low income countries
- Micro level access to affordable and reliable supply

Ensuring stable supplies are considered on both short and long time horizons. To deal with short term disruptions, actions generally focus on establishing strategic reserves in several countries, who can afford to do this. For oil in the OECD countries, the International Energy Agency co-ordinates the use of member countries' emergency oil stocks. Governments often have contingency plans to curtail consumption in order to deal with disruptions of supply.

For the longer term aspect of energy supply security actions generally focus on establishing policies tackling the root causes of energy insecurity in OECD countries, which can be separated into four broad types [4]:

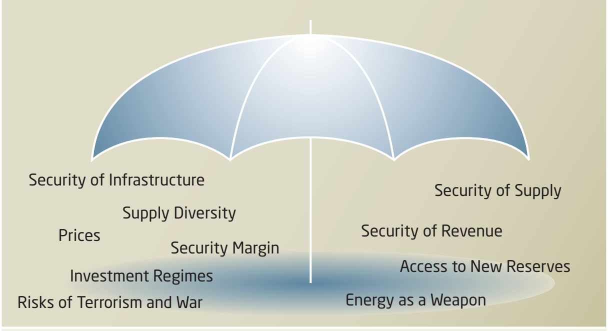
1. Concentration of fossil fuel resources: Government action aims to minimize the exposure to resource concentration risks in fossil fuel markets and includes moving away from fossil fuels, or diversifying supply routes and means
2. Energy system disruptions linked to extreme weather conditions or accidents: Government policies are generally precautionary in nature. Governments notably have an important role in preparing contingency arrangements for the management of, and recovery from, such incidents after they happen
3. Short-term balancing of demand and supply in electricity markets: governments may for example establish independent transmission system operators (TSO) responsible for the short-term balancing of demand and supply
4. Regulatory failures: Government action aims to monitor the effectiveness of regulations and to adjust regulatory structures when inefficiencies are detected

This approach to analyzing energy security helps identify areas where synergies best can be found with policies and measures to reduce energy-related greenhouse gas emissions. Policies addressing security concerns related to resource concentration generally have the most obvious opportunities for also addressing climate change mitigation, e.g. increasing renewable energy supply or increasing efficiency of production and use of energy.

In contrast, interactions with policies correcting for regulatory failures may have only secondary effects on greenhouse gas mitigation policies. Finally, energy security measures responding to the risks of short-term physical disruptions and the balancing of electricity grids have very limited direct interactions with climate mitigation efforts.

A similar but slightly more encompassing approach to energy security is included in the World Economic Forum publication "the New Energy Security Paradigm" (See Figure 2) [5].

Figure 2
Energy security: An umbrella term



Source: Cambridge Energy Research Associates [5]

The WEF approach also addresses the more political concerns, which do not come out in a more technical discussion, like geopolitical stability and use of control of energy resources as a political tool.

The major reasons for increased concern about energy security in the last years stem from a mixture of old and new causes.

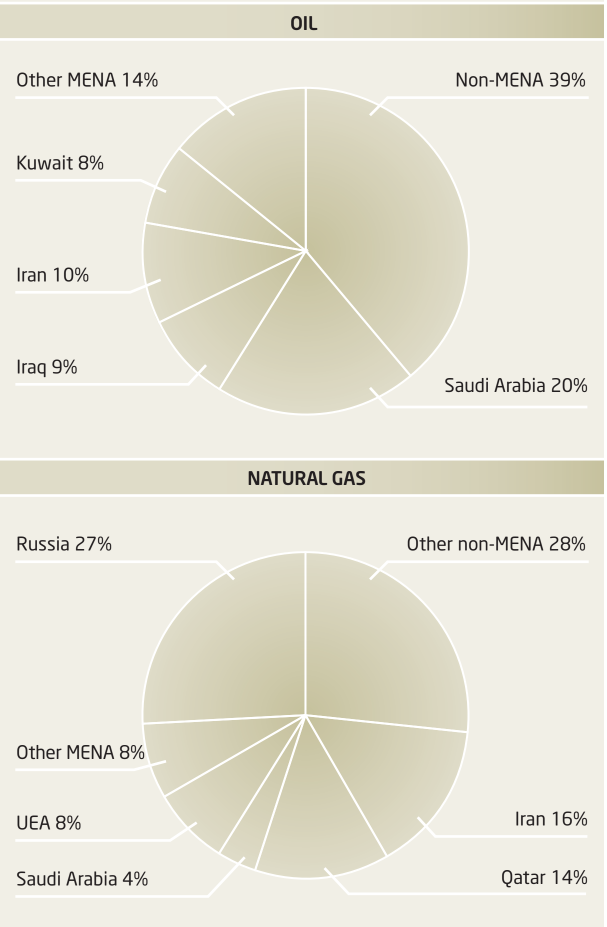
The "traditional" concern - like in the seventies and early eighties - about stability of oil supply combined with the major increase in oil prices in the last years are clearly major drivers. The overall oil intensity (oil consumed per unit of economic output) of the global economy has however declined by a factor of three over the last 25 years making many especially developed economies less vulnerable to fluctuations in oil markets. The transport sector is a special concern in relation to oil, as the dependency is virtually 100% and while biofuels, batteries and hydrogen are options for the future the current situation is an almost total dependency on oil.

The gas market has in the same period grown significantly and is gradually globalizing in terms of supply infrastructure although piped supply is still dominant. For example for the EU countries the import dependency is around 75% for oil and over 50% for natural gas and when the location of future reserves is analyzed it portrays a picture of further concentration of supply of both oil and gas, shown in Figure 3.

Diversifying oil and gas supply sources is one strategic approach to enhancing security for many countries and recent political interest in Africa by USA, EU and China illustrates more energy security concerns than concerns about African development per se.

On the consumption side the OECD countries have until recently experienced relatively stable growth with linked expansion of energy consumption in most countries. At the same time the large emerging economies like China and In-

Figure 3
Share of global oil and gas reserves in the Middle East and North Africa is much higher than its share of current production. [6]



dia have over the last couple of years become significant net importers and with both population and economic growth this trend is expected to accelerate the coming decades and is already reflected in how these large countries operate strategically on the global energy market (Figure 4).

In addition to the overall supply and demand changes there have also been a number of incidents in recent years in terms of political and natural events that have had major impact on the supply situation of oil. The Iraq war and hurricane Katrina are two extreme cases, but there are numerous smaller and less spectacular examples. Similarly the changing institutional ownership and market structures in many regional power markets have changed operations and regulation with some isolated but spectacular examples of black outs in large sub-regions.

So overall the concerns over energy supply security have become more complex and multi-faceted and many governments are still struggling to find the most effective solutions.

3.2.2 Developing economies

The previous sections are mainly reflecting concerns as they are seen from a "G8 + 5" perspective and while global demand and supply changes do affect all countries. The concept of energy security in most developing countries is much more associated with affordability of imported fossil resources or optimizing the rate of exports for fossil fuel producers and finally providing access to modern forms of energy for the poorest parts of the population.

Studies by the World Bank indicate that higher oil prices are causing many net oil importing Sub-Saharan African countries to lose economic ground — costing them a cumulative loss of over 3 percent of gross domestic product (GDP) — and increasing poverty in those areas by as much as 4 to 6 percent [7]. Evidently the oil exporting countries are experiencing a windfall profit situation and focus in this limited number of developing countries will evidently be on investing the revenues in securing future development also beyond the current fossil dominated period.

The present "oil crisis" has however in some African countries not had as severe effects as those experienced during the oil price hikes in the seventies and early eighties. In general the share of oil import costs as part of the overall imports has declined. For example in Tanzania where it has gone from a share of 70% to now around 20%. Higher prices on locally produced non-oil commodities have also helped compensate import costs associated with the oil price increase in a number of countries [8].

3.2.3 Danish perspectives

The Danish energy policy situation is in many ways a reflection of the joint EU priorities and reflects in many ways the discussions above about combining climate change and energy security priorities. The approaches and tools embedded in the national energy strategy for 2025 [9] and most recently elaborated in a more detailed political agreement for the coming 5 years include:

- Increased use of renewable energy especially wind and biomass
- Increasing overall energy efficiency
- Special efforts for reducing oil consumption in transport
- Development and implementation of innovative policy tools to make this happen
- Support for increased R & D in renewable energy and energy efficiency

Table 2
Key figures in Denmark's National Allocation Plan 2008-12 [9]

	Expected annual CO_2 emissions 2008-12 (mill. tonnes)	Annual allowance allocation 2008-12 (mill. tonnes)	Annual allowance allocation 2005-07 (mill. tonnes)
Electricity and heat production	20.5	15.8	21.7
Other industries, including offshore	9.2	8.2	9.2
New enterprises		0.5	1
Auctioning		0	1.7
Total CO_2 emissions/allowances in ETS sectors	29.7	24.5	33.5
Non-ETS sectors and gases in total [1]	38.1		
Total greenhouse gas emissions [2]	67.8		
Emissions target	54.8		
Deficit	13.0		

Notes: [1]: Stated in CO_2 equivalents. Includes emissions of CO_2 by non-ETS sectors and emissions of other greenhouse gases than CO_2 by ETS as well as non-ETS sectors.
[2]: Stated in CO_2 equivalents.

Table 3
Closing the gap – options for Denmark meeting its Kyoto target. How the deficit will be eliminated [9]

	Mill. tonnes annually
Deficit	13.0
Central government initiatives, including	-6.8
– monitoring CO_2 removals by sinks	-2.3
– new national measures within non-ETS sectors	-1.3
– JI/CDM credits, 2003-07	-3.2
To cover possible losses if, contrary to expectation, Denmark does not get compensation for the reference year, and/or to cover uncertainty in projections, inclusion of sinks ect., including	
– contributions from JI/CDM credits from 2008-09 resources	-0.3
– resources in reserve under section 35 of the Finance Act	-0.7
Central government initiatives in total	-7.8
Enterprises' commitment, including	-5.2
– electricity sector	-4.4
– other ETS enterprises (net) [1]	-0.8
Total	0

Notes: [1]: A pool of 0.5 milion tonnes/year for new entrants will be established, deducted from other enterprises' net contribution.

The agreement includes specific targets of a 20% share of renewables in the Danish energy system by 2011 and reduced gross energy consumption by 2% in 2011 and 4% in 2020. The most direct driver currently is probably climate change with the already existing commitments under the Kyoto protocol and joint EU policy targets mentioned above combined with the joint climate target on 20% reductions of GHG emissions by 2020.

The latest analysis from the European Environment Agency (EEA) shows that while many of the EU member countries have achieved their targets there are still a number of countries that have a long way to go [10]. Denmark is still approx. 11% from the target but with current plans and measures the EEA expects Denmark to meet its target (Fig. 5). The two tables from the Danish National Allocation Plan show in Table 2 the domestic measures including what will be achieved

Figure 4
Oil import projections for major countries and regions [6]

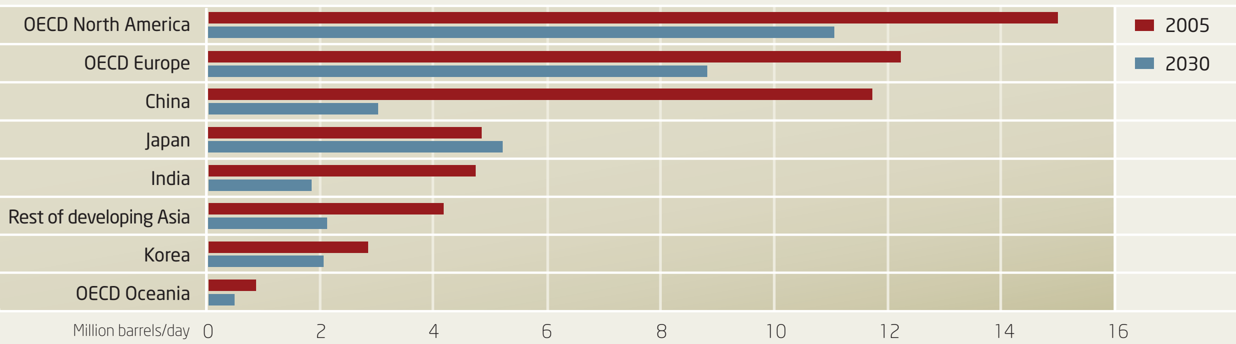
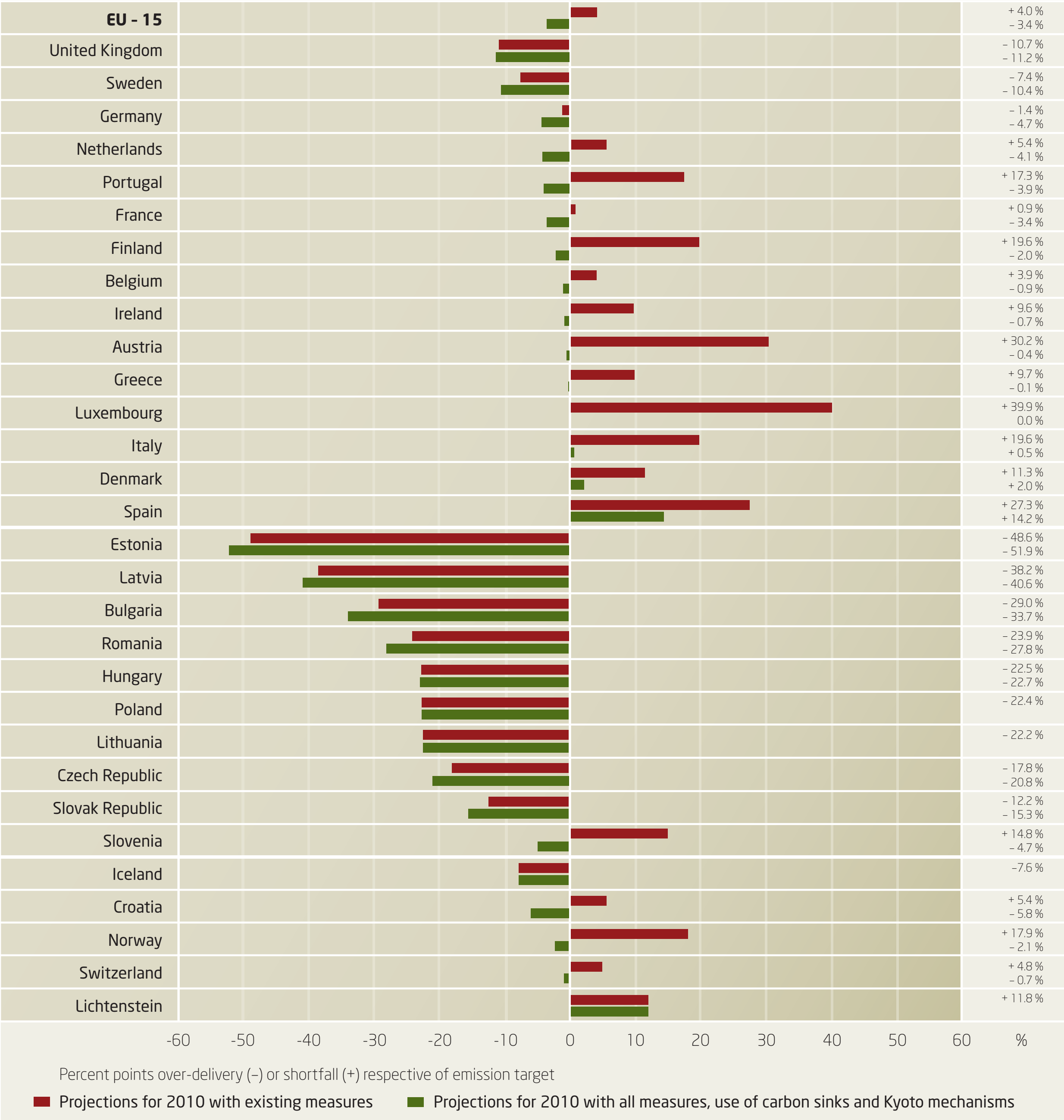


Figure 5
EU status on Kyoto goal achievement in 2008 [10]



through companies participating in the EU Emission Trading Scheme (ETS). Table 3 shows how the "deficit" will be met through additional measures and trading [9].

The specific approaches to address climate change and energy security evidently have to reflect the specific national circumstances and the Danish example only illustrates one approach, one which with all its proposed actions will address both concerns at the same time, as compared to other opportunities like increased domestic production of oil and gas which would increase short term energy security by reducing imports of coal etc. but have no longer term security value and very limited effect on climate mitigation efforts.

Whether the measures to close the gap will suffice remains to be seen and as indicated in the EU environment data in Fig. 5 their analysis indicates the resulting emissions will be close to the target, but may just fall short, However, this will depend on specific assumptions that differ from those of the Danish Government.

3.2.4 Concluding remarks

Political, economic and environmental drivers have moved energy to the forefront of international politics in recent years and 2007 was a clear example of this with an unprecedented focus on climate change worldwide and at the same time significant concerns about impacts of the growing oil and gas prices and the associated impacts on many societies.

The EU has taken the political lead globally with agreements on ambitious targets for GHG reductions combined with specific targets for the increased contribution of renewable energy in the energy supply within the Union. The US has focused much more on domestic energy security with the rapid increase of corn based bio-ethanol as a clear example of policy action that addresses this concern but has very little contribution to GHG reductions and longer term supply stability. China has developed a very diversified approach reflecting its very rapidly growing economy and associated energy demand expansion, this includes ambitious targets for renewable energy and energy efficiency, increased domestic production and establishing collaboration with a larger and more diversified group of oil and gas producing countries, most clearly exemplified by the strong expansion of collaboration with African countries. India has embarked on similar strategies, while less ambitious, but it has increased its interests and investments in neighboring countries like Bangladesh and Burma on gas and Iran, Syria and Sudan on oil supply options.

The strong international focus on climate and security has reduced the political focus on energy access in the poorest countries, so while some progress is achieved in selected countries there is overall not any major improvement in this area.

As the previous sections have shown, however, decisions on energy policy are subject to many regional and national priorities. Finding a global energy development path that satisfies all three concerns, especially climate change, is a major challenge that requires coordinated action from all countries.

Catalogue of energy technologies 4

Flemming J. Frandsen, Kim Dam-Johansen, DTU Chemical Engineering; Henrik Carlsen, Brian Elmegaard, DTU Mechanical Engineering; Hans Larsen, Leif Sønderberg Petersen, Risø DTU

The following chapter presents the status of R&D in progress for selected supply technologies and energy enabling technologies (energy enabling technologies are technologies with a function as enablers for other energy sources such as wind), and energy savings and efficiency improvements, based on the more detailed descriptions in Risø Energy Report 6, published in 2006 [1].

The chapter presents an overview (Table 4, see pages 30-31), which lists the technologies and provides a number of key facts for each technology, among others the potential contribution to future CO_2 reductions.

The presented technologies are assessed with respect to technological status and development, estimated time to contribution on commercial conditions, market development, challenges and barriers, CO_2 reduction potential, needed investments in research, demonstration and commercial production facilities, Danish strengths and possibilities in developing the technology, the technology's potential contribution in Denmark and globally, and finally adverse effects. The technologies are categorised in the following way:

Energy supply

Wind

Photovoltaics

Solar thermal

Biofuels for transport

Thermal fuel conversion technologies for fossil fuels and biofuels

Nuclear energy

Fusion energy

Geothermal energy

Hydro, ocean, wave and tidal

Energy enabling technologies

Fuel cells

Hydrogen generation

CCS (carbon capture and storage)

Energy storage

Heat pumps

Energy savings and efficiency improvements

Savings in new buildings, in retrofitting old buildings, LED lighting, efficiency in the transport sector etc.

4.1 Energy supply

4.1.1 Wind

Wind energy is a mature option in sustainable energy with great potential and a rapid development over the past 25 years. In 2007 the installed capacity in Denmark was about 3 GW and wind turbines produced electricity equal to 20% of the total Danish electricity demand. In 2008 the global installed wind power capacity was about 100 GW [2, 3]. For some years, world wind capacity has been doubled every three to four years. In the years ahead the growth rate is expected to be higher in the USA and Asia. Despite this technological development, and rapid growth in a few countries, wind today provides only a small percentage of the world's electricity.

Assuming further rising primary energy prices, wind turbines are approaching the point where they can compete economically with conventional power production. A recent analysis from the EA Energy Analyses for Danish Energy Association concludes that offshore wind turbines will be competitive with other energy technologies in 2015 [4].

Denmark has a world leading position in wind energy research, development and production, but now several other countries record a fast development in the area of wind energy.

Globally there are many plans for wind energy R&D. UpWind is the largest EU initiative in wind energy R&D to date.

UpWind looks towards future wind power, including very large turbines (8–10 MW) placed in wind farms of several hundred MW in total, both on- and offshore. In the USA, the Department of Energy (DoE) has laid out a five-year plan for wind energy R&D [5]. The plan focuses on cost reduction, increased energy and reliability performance, and achieving 20 % of the electricity market by 2030 for onshore applications.

European countries and the EU as a whole are leading the deployment of wind energy. Today the industry produces wind turbines that take an active part in the control and regulatory functions of power systems. Turbine manufacturers will continue to develop these capabilities in response to new requirements in the grid codes – the rules that govern how generating equipment interacts with the transmission grid – for "fault ride-through" and power quality, and the increasing importance of short term wind forecasting. An important way to remove trade barriers and disseminate research results is to establish international standards for wind technology. Both national and European R&D programmes have supported this approach.

4.1.2 Photovoltaics

Photovoltaic (PV) devices, otherwise known as solar cells, convert light directly into electricity. PV technology is modular and contains no moving parts. Solar cells are commonly divided into at least three categories. First-generation solar cells are made from crystalline silicon. Second-generation PV uses thin-film technology, including amorphous silicon, CIS and CdTe. Third-generation technologies combine organics and semiconductors.

First-generation solar cells are currently dominant: crystalline silicon constitutes about 90% of the world market, and this situation is expected to continue until at least 2015. Second-generation solar cells are increasing in market share, with high-efficiency cells produced for high-value applications including satellites. Third-generation cells are still mostly at the research stage. Solar electricity is forecast to reach grid parity after 2016.

Solar cells were the fastest-growing renewable energy technology market in 2005, with a global annual growth rate of more than 40%, and this trend continued in 2006. Growth has been dominated by grid-connected distributed systems in Germany and Japan.

The status of PV technology, its potential and R&D challenges were addressed comprehensively by the EU-supported publication A Vision for Photovoltaic Technology compiled by the Photovoltaic Technology Research Advisory Council [6]. These R&D challenges are presently being analysed in more detail in a study called the PV Strategic Research Agenda (SRA), which was published in 2007 [7].

Solar cells are not produced in Denmark. One company has the potential to produce solar-grade.
Denmark has particular strengths in inverters, an essential support technology for solar cells. Net metering is now a permanent incentive in Denmark, and this allows long-term planning of PV investments.

Third-generation solar cells bring opportunities to integrate PV into other products via printing and plastics processing, and a number of Danish industries already have many of the skills needed to do this. PV is in the middle of a technological and commercial breakthrough, and new generations of technology promise a continued bright future. It is important to maintain Danish industrial competence in PV by securing a national market.

4.1.3 Solar thermal

Solar thermal heating is a long-established technology for space heating and domestic hot water. New applications are emerging for industrial processes, where solar energy could replace fossil fuels or electricity.

For solar thermal devices the average annual market growth rate has been 17–20% in recent years. The most dynamic market areas are China and Europe. In absolute terms the European solar thermal market is dominated by Germany (~50%), followed by Greece and Austria (~12% each). Europe's present solar thermal capacity provides around 0.15% of the overall EU requirements for hot water and space heating. The EU goal for solar thermal units is 100 million m² by 2010. However, with the present market trends only about 40 million m² is likely to be reached by 2010.

In general, costs per unit area decrease with the size of the system. Solar thermal systems connected to a district heating network are therefore more cost-effective than systems for single family houses. Solar thermal systems traditionally include short-term hot water storage capacity in the range 50–75 l per m² of collector. Seasonal storage of around 2,000 l per m² has been investigated, but is still considered to be at the R&D stage.

A relatively new market for solar thermal units is industrial process heat. Low-temperature process heat, in the range achievable by traditional solar collectors, is needed in many industries.
Concentrating solar power systems (CSP) can be sized for

village power (10 kilowatts) or grid-connected applications (up to 100 megawatts). Some systems use thermal storage during cloudy periods or at night. Others can be combined with natural gas and the resulting hybrid power plants provide high-value, dispatchable power. These attributes, along with high solar-to-electric conversion efficiencies, make concentrating solar power an attractive renewable energy option that is rapidly gaining momentum in the US. It could be viable in many parts of the world, but not so attractive in Denmark and the northern part of Europe.

4.1.4 Biomass based fuels for transport

There are several motivations to provide alternative transport fuels based on biomass as a raw material. It will be a transport fuel with low CO_2 emissions, it will reduce the dependence on imported fossil fuels in the Western world and it is possible to further develop a domestic industry based on liquid fuels. Liquid transport fuels based on biomass can be produced by several different means such as biodiesel from rape, ethanol by fermentation and by the GTL-technology (Gas-To-Liquid). The GTL-technology has the potential to obtain a high biomass to liquid conversion efficiency, and it should be possible to develop the technology so that a broad range of solid input fuels can be applied. A disadvantage is that GTL-plants are relatively large and complicated.

The GTL-technology uses natural gas or gas produced from solid fuels or from gasification of biomass, waste or coal, where it is converted to a gas rich in CO and H_2. This gas is then used for a synthesis of hydrocarbon liquids, by use of a catalyst. Depending on the catalyst type and operating conditions different products can be made e.g. ethanol, DME (dimethyl ether), higher alcohols, and Fischer-Tropsch gasoline or diesel. Often a pressurized oxygen blown entrained flow or fluid bed gasifiers is used to produce the synthesis gas. The gas supplied from the gasifiers to the catalytic synthesis does often need to be carefully conditioned in order to obtain an adequate H_2/CO ratio, and to be cleaned of species that might poison the catalysts.

The GTL-technologies are presently used on a large scale to produce methanol from natural gas, and for many years Fischer-Tropsch hydrocarbon production in South Africa. Because of the relatively high fossil oil prices, GTL-technologies have gained renewed global attention, and in China plants for DME production from coal are being erected. Large-scale commercial production of transport fuels from biomass with the GTL technology is not done presently, but the increased awareness of the need to reduce CO_2-emissions, and the need to provide alternative transport fuels, do strongly favour this technology.

A broad band of research work needs to be initiated to consolidate the GTL-technology for commercial application, improve energy efficiency and improve the possibilities to integrate the technology with other energy technologies. Possible research areas could be:

- Further development of pressurized gasifiers to handle biomass and waste as well as co-gasification of biomass and coal
- Work on integration of the GTL technology with power production so that waste heat can be used efficiently for power and central heat production. Integration with other advanced technologies so outlet CO_2-sequestration can be obtained and that the gasification can be integrated with combined cycle power production
- Increase of plant efficiency by improving the efficiency of both the gasification and synthesis process
- Development of new catalysts, with higher tolerance towards poisoning, and improved control over product composition
- Development and test of motors, and distribution sys tems, for new fuel types

The biological based production of transport fuels is often based on fermentation. Large scale commercial production of biofuels today mainly covers the production of bioethanol of the first-generation type, meaning that it is made from corn, wheat, sugar cane or sugar beet). The technology needed to make first-generation bioethanol from starch has developed rapidly, thanks to intensive research in enzyme technology.

Second-generation bioethanol is produced from plant sugar components in straw, wood chips, grasses, waste paper and other "lignocellulosic" materials. It requires more expensive methods to release and ferment the different kind of sugars. Today, lignocellulosic processing is well advanced, and the EU has three demonstration plants, one in Denmark.

By 2030 the European Union and the USA plan to meet 25–30% of their transport fuel needs with sustainable and CO_2-efficient renewable biofuels. Vehicles with ordinary gasoline engines can use a blend of gasoline with 10% ethanol (E10) while modified "flexi-fuel" engines can use E85 (85% ethanol and 15% gasoline). Neat ethanol (E100) can also be used in gasoline-type (Otto) engines with high compression ratios, and in diesel engines with the addition of an ignition enhancer. The actual critical discussion on biofuels in the EU will at least slow down the realisation of an area covering biofuel infrastructure.

The IEA (2006) has projected an average annual growth rate of 6.3% for liquid biofuels between 2005 and 2030, most of which will be in the form of ethanol [8].

4.1.5 Thermal fuel conversion – combustion, gasification and pyrolysis of biomass

The thermal conversion of biomass and waste into power, heat and process energy is today the world's largest contributor of CO_2 neutral energy and will also in the future provide a large share of CO_2 neutral energy supplies. A very broad range of thermal based technologies are used today, and some emerging thermal technologies will also be used in the future. This includes technologies as:

- Waste incineration based power and heat production
- Biomass power plants using both grate and suspension fired boilers and using different co-firing technologies
- Oxyfuel based combustion applied for carbon storage
- Large scale pressurized gasification as an integrated part of flexible high efficient power plants
- Small scale biomass gasification units applied for local power production
- Pyrolysis units used for production of bio-oil and transport fuels

Through cooperation between Danish research institutions and industry, Denmark has obtained a leading position in waste and biomass combustion technology; however, to maintain this position a high activity level and public sponsored research is also needed in the future.

A range of research challenges persists including: Increased biomass fuel share in power plant boilers, increased electrical efficiency of waste and biomass combustion plants and reduced operational problems, development of mature and flexible pressurized gasification technologies and development of reliable biomass pyrolysis reactors.

4.1.6 Thermal fuel conversion – fossil fuels

Modern industrial development is to a significant extent based on production of heat and electricity from combustion of fossil fuels like coal, oil and natural gas. One of the adverse effects is that combustion of fossil fuels is the largest source of carbon dioxide emissions. Fossil energy use is responsible for about 85% of the anthropogenic CO_2 emissions produced annually [9].

In industrial applications, by far the most common utilization of fossil fuel energy is combustion. Fossil fuels supplied 80% of the world's primary energy demand in 2004 and their use is expected to grow in absolute terms over the next 20–30 years in the absence of policies to promote low-carbon emission sources. Traditional biomass excluded, the largest constituent was oil, then coal (25%) and gas (21%). Natural gas is the fossil fuel that produces the lowest amount of GHG per unit of energy consumed and is therefore favoured in mitigation strategies [9].

Coal is the most abundant fossil fuel, with widespread resources all over the world – enough to last several hundred years with the current consumption rate. Due to this, coal shows better price stability than oil and gas, and has gained renewed interest as an energy source over the past decade. Coal is mainly applied as a solid fuel to produce electricity and heat through combustion. Most of the energy supply in Denmark comes from combustion of pulverized coal, and the Danish power plants are leading worldwide with respect to energy efficiency of these plants. Nevertheless, coal will only be an option for the future if it is feasible to reduce the emissions of CO_2 cost-efficiently.

Approximately 40% of the world electricity production is based on coal. The total known deposits recoverable by current technologies, including highly polluting, low energy content types of coal (i.e. lignite, subbituminous), might suffice for around 300 years of use at current consumption levels, though maximal production could be reached within decades.

When coal is used for electricity generation, it is usually pulverized and blown in suspension into a furnace where it reacts with primary and secondary air. The furnace is equipped with a steam cycle (boiler). The furnace transforms chemical energy in the coal to heat in a hot flue gas. The heat from the hot flue gas is subsequently applied to convert boiler water to steam, which is then superheated and in a series of steps used to spin turbines which turn generators and create electricity. The thermodynamic efficiency of converting coal to electricity has improved significantly over time. The most advanced standard steam turbine reached about 35% thermodynamic efficiency for the entire process, which means that 65% of the coal energy is waste heat released into the surrounding environment. Old coal-fired power plants are significantly less efficient and produce higher levels of waste heat. Supercritical turbine concepts are predicted to run a boiler at extremely high temperatures and pressures with projected efficiencies of 46%.

Other efficient ways to use coal are combined cycle power plants, combined heat and power cogeneration, and an MHD topping cycle. The MHD (magnetohydrodynamic) generator converts thermal energy or kinetic energy directly into electricity. MHD generators can operate at high temperatures without moving parts. The exhaust of a MHD generator is a flame, still able to heat the boilers of a steam power plant. So high-temperature MHD could be as a topping cycle to increase the efficiency of electric generation, especially when burning coal or natural gas. This technology is still far from commercial status.

Natural gas presently accounts for 21% of global consumption of modern energy. Natural gas-fired power generation has grown rapidly since the 1980s because it is relatively superior to other fossil-fuel technologies in terms of investment costs, fuel efficiency, operating flexibility, rapid deployment and environmental benefits, especially when fuel costs were relatively low. Combined cycle gas turbine (CCGT) plants produce less CO_2 per unit energy output than coal or oil technologies, because of the higher hydrogen-carbon ratio of methane and the relatively high thermal efficiency of the technology [9].

Conventional oil products extracted from crude oil-well bores and processed by primary, secondary or tertiary methods represent about 37% of total world energy consumption with major resources concentrated in relatively few countries. Assessments of the amount of oil consumed, the amount remaining for extraction, and whether the peak oil tipping point is close or not, have been very controversial. Now 30 to 40 years' supply is a reasonable estimate. Unconventional liquid fuels, i.e. oil that requires extra processing (heavy oils, oil (tar) sands or from shales), will then become more economically attractive. Resource estimates are uncertain, but together contributed around 3% of world oil production in 2005 (2.8 EJ) and could reach 4.6 EJ by 2020 and up to 6 EJ by 2030 [9].

4.1.7 Combustion

Direct combustion of fuels may in principle occur in one of the following technologies; fixed-bed firing on a grate, fluidized bed combustion or (co-)firing in suspension. Each of these technologies poses different characteristics and is well-suited for fuels of quite different physical and chemical composition. In order to increase the total plant efficiency, most modern boilers (except for waste incinerators outside of Europe and Japan) produce both heat and power.

An energy-efficient way of using coal for electricity production would be via solid oxide fuel cells or molten carbonate fuel cells (or any oxygen ion transport based fuel cell that do not discriminate between fuels, as long as they consume oxygen), which would be able to reach 60%–85% combined efficiency (direct electricity + waste heat steam turbine). Currently these fuel cell technologies can only process gaseous fuels, furthermore they are sensitive to sulfur poisoning; this operational problem must be solved before large scale commercial success is possible with coal. As far as gaseous fuels go, one possible solution is pulverized coal in a gas carrier, such as nitrogen. Another option is coal gasification with water, which may lower fuel cell voltage by introducing oxygen to the fuel side of the electrolyte, but may also greatly simplify carbon sequestration.

4.1.8 Gasification

Industrial-scale gasification is currently mostly used to produce electricity from fossil fuels such as coal, where the syngas is burned in a gas turbine. Four types of gasifier are currently available for commercial use: counter-current fixed bed, co-current fixed bed, fluidized bed and entrained flow. Gasification is also used industrially in the production of electricity, ammonia and liquid fuels (oil) via Integrated Gasification Combined Cycles (IGCC), with the possibility of producing CH_4 and H_2 for fuel cells. IGCC is also a more efficient method of CO_2 capture as compared to conventional technologies. IGCC demonstration plants have been operating since the early 1970s and some of the plants constructed in the 1990s, are now entering commercial service. In the early research stage is microbes for the in-situ-coal mining producing methane as a product of digestion.

4.1.9 Reduction of emissions

Many techniques for NO_X- and SO_X-removal from flue gases have been developed over the last decades. Nowadays the preferred technologies are selective catalytic reduction (SCR) with NH_3 for NO_X conversion to N_2 and wet gypsum producing SO_2 reduction by limestone.

Reductions in CO_2 emissions can be gained by improving the efficiency of existing power generation plants by employing more advanced technologies using the same amount of fuel. For example, a 27% reduction in emissions (gCO_2/kWh) is possible by replacing a 35% efficient coal-fired steam turbine with a 48% efficient plant using advanced steam, pulverized-coal technology. Replacing a natural gas single-cycle turbine with a combined cycle (CCGT) of similar output capacity would help reduce CO_2 emissions per unit of output by around 36%. Switching from coal to gas increases the efficiency of the power plant because of higher operating temperatures, and when used together with the more efficient combined-cycle results in even higher efficiencies [9].

4.1.10 Nuclear energy

Nuclear fission energy is a major CO_2 emission-free energy source; it provides 15% of the world electricity production and 7% of the total energy consumption. Globally, 440 reactors are in operation in 31 countries with most of the nuclear generation capacity being in Europe, the US, and Southeast Asia. Due to the high capital cost of nuclear reactors and low fuel prices nuclear energy is used predominantly for base load electricity production. In Europe, nuclear accounts for 20% of the generation capacity but provides 31% of the electricity generation.

The technology is fully developed and available to the market. However, the majority of existing nuclear power units was built in the 1970s and 1980s. After 1990, nuclear power globally faced stagnation. Construction of nuclear power plants, however, continued in the Far East, especially in Japan and South Korea. Since 1990 the global installed capacity has increased only slightly to the present value of 370 GWe.

Nuclear power is not vulnerable to even high fuel price fluctuations, and as it is based on uranium sources that are widely distributed around the globe, fuel supply is not strongly affected by geopolitical issues. In addition, because many years' worth of nuclear fuel can be stored in a small area, the presence of local uranium resources is not a pre-condition for nuclear energy security.

Most projections from IEA, IPCC and others expect some growth in the installed capacity of nuclear energy in the coming decades, with large regional differences and from country to country, primarily due to the public acceptance issue. A growing number of countries in Asia, e.g. Indonesia, Thailand and Vietnam, are seriously considering or planning to use nuclear energy for electricity generation. India and the US have agreed to cooperate in increasing the nuclear power generation capacity in India. The nuclear option is primarily considered for energy security purpose at present. The nuclear option is expected to be even more attractive in countries like China and India concurrently with agreements on CO_2 reduction targets.

Nuclear power does not form part of the Danish energy mix and at present there seems to be little political will to change this position. As a result, Denmark has relatively little expertise in nuclear power and no university courses for nuclear engineers. Denmark maintains limited preparations for a nuclear emergency besides monitoring for anthropogenic radioactivity in the environment.

4.1.11 Fusion energy

A fusion reactor would "burn" the isotopes deuterium and tritium at moderate pressure and at a temperature of 150 million Kelvin. A fusion reactor will produce much less radioactive waste than a fission reactor. Fusion plants are inherently safe as the reactor only contains enough fuel to feed the fusion processes for the next few seconds. The main cost of fusion energy will be in constructing the power plant, while the cost of fuel is negligible. Fusion power will therefore be most economical when run as base load, though it can easily contribute to a sustainable energy mix.

Estimation of cost per ton CO_2 reduction is premature due to the state of development of the technology. In IPCC AR4 fusion power is regarded as basic research at the moment, hence cost estimates are not included. Fusion offers a safe, clean, zero-CO_2 energy source, burning fuel that is abundantly available everywhere that may be ready to make a large contribution to world energy production in the second half of this century. A realistic size for a fusion plant is 1,500 MWe. Such power plants could be built throughout the world including in Denmark.

The design and building of the largest fusion reactor ITER has begun in broad international cooperation. The ITER is projected to start operating in 2016. The next step is likely to be a demonstration fusion power plant called DEMO. To make use of the results from ITER, the construction of DEMO will probably not start until some years after ITER starts operating, most likely not before 2025.

As a part of the European fusion research programme Denmark makes significant contributions to the field of research. In many of these areas Danish industry is in a strong position to enter into industrial contracts. This involvement of Danish industry is facilitated by Risø DTU.

4.1.12 Geothermal energy

Geothermal energy is heat from within the earth. The steam and hot water produced inside the earth can be used to heat buildings or generate electricity. Geothermal energy is a renewable energy source because the water is replenished by rainfall and the heat is continuously produced inside the earth.

The main uses of geothermal energy are:

- Direct use and district heating systems which use hot water from springs or reservoirs near the surface
- Electricity generation in a power plant requires water or steam at very high temperature (300 to 700 degrees Fahrenheit). Geothermal power plants are generally built where geothermal reservoirs are located within a mile or two of the surface
- Geothermal heat pumps use stable ground or water temperatures near the earth's surface (less than 100 metres) for space heating

Installed geothermal generating capacity in the EU was 893 MWe in 2005, mostly in Italy and Iceland. European production of geothermal energy for heating was 2.3 Mtoe in 2005. Most geothermal heat is produced in Turkey and Iceland. The first plant in Denmark opened in 1984 in Thisted. The second, which opened in 2005 at Margretheholm, supplies 1% of the total heat demand in Copenhagen.

The resources are huge in many parts of the world, hence only market conditions sets limits for the application.

In its Alternative Policy Scenario, the International Energy Agency (IEA) assumes an installed capacity of 3,000 MWe in OECD Europe by 2030 [8]. Today the technology to extract heat from underground aquifers is well known, but the energy available at shallow or moderate depths is limited, However, a huge energy resource exists at greater depths, including in Denmark.

Denmark has huge potential for geothermal energy, and high oil prices have encouraged an increasing number of cities to embark on geothermal projects. It is difficult, however, to predict the share of geothermal energy in the future Danish energy system. In some countries, including Denmark, geothermal energy is not available at a high enough temperature for electricity production. District heating systems based on heat pumps, however, can make good use of low-temperature geothermal energy.

4.1.13 Hydro, ocean, wave and tidal

This group of energy supply technologies is based on the use of potential, kinetic or thermal energy of water as energy source and show different stage of development. Hydro power and pumped hydro storage systems have for many years been fully commercially competitive in many parts of the world. On the other hand ocean energy, including wave and tidal are at an early stage of development.

OECD and non-OECD countries produce roughly equal amounts of hydroelectricity. Little growth is expected in OECD countries, where most hydro potential has already been realised: on average, capacity has increased by just 0.5% annually since 1990. The OECD nations produced 1,343 TWh of hydroelectricity in 2003, the largest contributors being Canada (338 TWh), the USA (306 TWh) and Norway (106 TWh).

Large hydro remains one of the lowest-cost generating technologies, although environmental constraints, resettlement impacts and the limited availability of sites have restricted further growth in many countries. Large hydro supplied 16% of global electricity in 2004, down from 19% a decade ago. Large hydro capacity totaled about 720 GW worldwide in 2004 and has grown historically at slightly more than 2% annually. China installed nearly 8 GW of large hydro in 2004, taking the country to number one in terms of installed capacity (74 GW). With the completion of the Three Gorges Dam, China will add some 18.2 GW of hydro capacity in 2009.

Small hydropower has developed for more than a century, and total installed capacity worldwide is now 61 GW. More than half of this is in China, where an ongoing boom in small hydro construction added nearly 4 GW of capacity in 2004. Other countries with active efforts include Australia, Canada, Nepal and New Zealand.

Ocean currents, some of which run close to European coasts, carry a lot of kinetic energy. Part of this energy can be captured by submarine “windmills” and converted into electricity. These are more compact than the wind turbines used on land, simply because water is much denser than air. The available power is about 1.2 kW/m^2 for a current speed of 2 m/s, and 4 kW/m^2 for a current of 3 m/s. The main European countries with useful current power potential are France and the UK.

Ocean tides can be exploited for only four or five hours per cycle, so power from a single plant is intermittent. A suitably designed tidal plant can, however, operate as a pumped storage system, using electricity during periods of low demand to store energy that can be recovered later. The only large, modern example of a tidal power plant is the 240 MW La Rance plant, built in France in the 1960s, which represents 91% of world tidal power capacity.

Wave energy can be seen as stored wind energy, and could therefore form an interesting partnership with wind energy. Waves normally persist for six to eight hours after the wind drops, potentially allowing wave power to smooth out some of the variability inherent in wind power.

Wave power could in the long term make an important contribution to the world's energy demand, if it can be developed to the point where it is technically and economically feasible. A potential 2,000 TWh/year, or 10% of global electricity consumption, has been estimated, with predicted electricity costs of €0.08/kWh. Wave power is an energy source with a low visual and acoustic impact. Oceanic waves – those occuring far offshore – offer enormous levels of energy; power levels vary from well over 60 kW per metre of wave front in the North Atlantic to around 20 kW/m nearer shore.

Wave power is being investigated in a number of countries, particularly Japan, the USA, Canada, Russia, India, China, Portugal, Norway, Sweden, Denmark and the UK. At present, the front runners are Portugal and the UK.

In contrast to other renewable energy sources, the number of concepts for harvesting wave energy is very large. More than 1,000 wave energy conversion techniques have been patented worldwide, though they can be classified into just a few basic types:

- Oscillating water columns (OWCs)
- Overtopping devices
- Heaving devices
- Pitching devices
- Surging devices

Wave power has gained renewed interest in Denmark. Examples are Wave Dragon and Wave Star. These demonstration projects are very successful as a starting point for the commercial development of this technology.

4.2 Energy enabling technologies

4.2.1 Fuel cells

Fuel cells are at the point of breakthrough as a most versatile and efficient energy conversion technology. They have strong links with renewable technologies, such as wind, solar and wave power, and they will be central to any future "hydrogen society", with its promise of a release from dependence on fossil fuels. Denmark is playing a significant role in the development of fuel cells, all the way from fundamental research to consumer applications.

Low-temperature fuel cells, notably PEMFCs could replace car engines and are already being used in commercial uninterruptible power supplies, such as those made by the Danish company Dantherm.

High-temperature fuel cells (solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) are fuel-flexible, highly efficient and environmentally clean. They can run on fuels such as natural gas, biogas and methanol. Risø is one of the leading developers of SOFCs, in collaboration with Topsoe Fuel Cell A/S.

The application areas for fuel cells fall into three main markets: stationary, transport, and portable. The stationary market ranges from small (≤1 - 5 kW) CHP units for single households to 100-1000 kW CHP units for district heating; and multi-MW units for power generation. Fuel cells may become important in the transportation sector in hybrid cars, buses, trucks and trains. The first commercial fuel cells are now appearing in portable applications and backup power systems.

The main drivers in favour of fuel cells are:

- High electrical and total efficiency, even in small sizes, allowing for application of cogeneration in small buildings
- Ability to use renewable, locally-produced fuels, and thus reduce dependence on imported fossil fuels
- Siting near the point of use eliminates or considerably reduces distribution losses for both heating and electricity
- Important as an enabler for other renewable energy sources such as wind
- Can be used to help the world meet its increasing de mand for energy
- Creates employment opportunities for skilled labour and a basis for export of value added goods

By 2015 many developers foresee production capacities in the 100 MWe/y range, and forecasts for 2025 are in the GWe/y range. In the very long term, the world wide potential for fuel cells in power generation is more than 100 GWe/y. Fuel cells in the transportation sector will begin with their use as APUs in about 2020, followed by fuel cell hybrid vehicles in approximately 2025.

The high electrical efficiency and reduced transmission losses promised by fuel cells translate directly to lower CO_2 emissions. The amount of CO_2 reduction depends on the scenario chosen, especially the fuels used, but the potential savings run into millions of tonnes of CO_2 per year in Denmark alone.

4.2.2 Hydrogen

Hydrogen is an energy carrier, not an energy source. Realizing hydrogen as an energy carrier depends on low-cost, high-efficiency methods for production, transport and storage. Hydrogen can be produced by many technologies, based on fossil and sustainable fuels. Thermal and thermochemical processes use heat to release hydrogen and are the most mature technologies. Electrolytic processes use electricity to produce hydrogen. Here renewable sources such as wind can be considered. An electrolyser is based on the same principles as a fuel cell, but the process is reversed, i.e. electricity is used. Electrolysis will likely play an important role in any future non-fossil energy scenario, not only in the hydrogen society. Current costs of electrolysers are high but declining. The degree of sustainability of the hydrogen production strongly depends on the feedstock used. Ultimately, hydrogen fuel could be produced in association with CCS leading to low-emission transport fuels. Photolytic processes offer a challenging, long-term potential for a sustainable hydrogen production and have to be further developed.

In a world wide perspective, the United States has the most significant hydrogen and fuel cell programs. The management of funds for development of hydrogen production and storage technologies is provided by the Department of Energy (DoE). The DoE Office of Energy Efficiency and Renewable Energy has an actual funding for hydrogen R&D, which includes fuel cells on $US 194 million in 2007 and $US 211 million in 2008.

At the EU level, research funds for hydrogen and fuel cells have increased over the years in the Framework Programmes. The development of a hydrogen economy, with H2 produced from renewable energy sources, is a long-term objective of the European R&D agenda, and substantial funds have been allocated over the years to pave the way. A Joint Technology Initiative (JTI) for Fuel Cells and Hydrogen will be established in order to establish a public-private partnership on the European level. The budget will be in the range of 80-100 million Euro/year.

A Strategic Research Agenda as well as a Deployment Strategy were endorsed by the managing body of the European Technology Platform for Hydrogen and Fuel Cells in 2004. An Implementation Panel was established in 2006 to take the strategy for research and demonstration of hydrogen and fuel cells technologies to the implementation stage by 2010-2015. This will require an estimated investment of 7.4 billion Euro between 2007-2015.

At the national level, the Danish Energy Authority, together with other energy research funding agencies, published a strategy in 2005 [10]. The strategy estimates a total investment of 1.5-2.0 billion DKK over a 10-year period. In 2006, the Danish partnership for Hydrogen and Fuel Cells was established with the aim to promote the technological development. A first important step to realise this strategy has been made by the proposed governmental RD&D programme for new energy technologies with an estimated public investment of 477 MDKK for the period 2007-2010. Most important, a national hydrogen technology platform with the participation of public authorities, research institutes and private companies develops research, development and demonstration projects in selected key hydrogen and fuel cell energy technologies.

The long-term vision of the hydrogen economy will take several decades to be achieved.

4.2.3 Carbon capture and storage

Carbon dioxide (CO_2) capture and storage (CCS) is a process in which CO_2 is separated from sources such as big boilers, and held in long-term storage instead of being released to the atmosphere. CCS could be applied in large scale units in the power sector and in energy dense industry. Captured CO_2 may be stored in geological reservoirs such as oil wells or aquifers, or on the ocean floor; or it may be chemically fixed, by converting it into solid substances known as inorganic carbonates.

Capturing, transporting and storing CO_2 carries an energy penalty: a plant with CCS will consume roughly 10– 40% more energy than a similar plant without CCS. The net reduction in CO_2 emissions to the atmosphere therefore depends upon the fraction of CO_2 captured, the increased CO_2 production necessitated by the energy penalty, and any CO_2 leakage during transport and storage.

Capture is the most energy-intensive process in the whole CCS chain. CCS costs are projected to fall, however, with further R&D and economies of scale as more plants are built.

The CCS and coal is an important combination, e.g. IGCC, as it is less expensive to extract CO_2 upfront from the gasification stage than from the flue gas as in the case of CCGT. US Future-gen initiative and the CO_2 pumping in the Texas oil fields are interesting developments internationally.

For geological reservoirs the fraction of CO_2 retained is very likely to exceed 99% over 100 years.

Large-scale injection of CO_2 into the ocean could make the seawater more acidic, with damage to local marine life.

The European Community is active in CCS R&D through the Framework Programmes.

Energy systems of some large developing countries such as China, India and South Africa have strong coal dependence and therefore CCS could play a critical role in mitigating their GHG emissions while maintaining their coal dependence in the future.

At the global level, several European countries are active in the Carbon Sequestration Leadership Forum. At the moment these nations are Denmark, Germany, France, Italy, Norway, the Netherlands, the UK and the European Commission.

At the Danish coal-based power plant Esbjergværket the world's largest post-combustion capture test facility has been in operation since March 2006.

CCS is a promising technology for greenhouse gas mitigation, so investing in CCS R&D could prove to be good for Danish industry in the short and medium term. There are opportunities to market CCS globally, including in large developing countries like China and India. Denmark's strength in technologies such as very-high-efficiency coal combustion for power generation, research on new adsorbents for CO_2 capture, and pre-combustion CO_2 capture through solid oxide fuel cells and oxygen membranes all have excellent market potential, and should therefore be pursued. For developing countries, CCS adsorbents that can handle dirty flue gas containing SO_X and NO_X could also be an interesting research opportunity. Collaboration with large consumers of coal, such as the USA, China, India, Australia and South Africa could provide good business opportunities, since a less expensive CCS could make an attractive GHG mitigation option.

4.2.4 Energy storage

The rationale behind storage of energy is:

- Potential economical savings
- Security of supply, or
- The possibility for storing renewable energy

In Denmark there is a significant focus on the introduction of more wind power as well as maintaining the security of supply in spite of the fluctuating wind power. For this reason significant efforts are done in order to develop an optimal storage system for electricity. Similar interests are observed in other EU countries and other parts of the world.

Storage of energy should be divided into different applications:

- Storage for heat supply
- Storage for electricity supply

For both applications several technologies exist for both large scale and small scale storage.

4.2.5 Heat storage

Within the energy system, storage of thermal energy for heating is used in industry for process heat, but significant energy savings may also be obtained by storing surplus heat as hot water, e.g. for use in cleaning in place (CIP) systems.

In combined heat and power and other district heating systems storage of heat in hot water tanks separates heat and power production and thus makes it possible to optimize operation strategies in both markets at maximum energy utilization. The energy utilization of thermal energy storage is generally close to unity, however the second law efficiency will be high only if small temperature differences are utilized.

Available technologies:

- Storage of sensible heat (water tank, gravel, soil)
- Storage of latent heat (enthalpy of fusion or evaporation, e.g. by zeolithes or molten salts)

4.2.6 Electricity storage

Electricity storage involves several storage technologies which all require one or more conversions of energy from electricity to the storage and back to electricity. The energy form used in the storage may be potential energy, chemical energy, thermal energy, kinetic energy or electrical energy. Some of the available technologies are:

- Pumped hydro storage
- Compressed air electricity storage (CAES)
- Batteries
- Flow batteries
- Flywheels
- Hydrogen generation by electrolysis and subsequent electricity production
- Superconductors

Only a few of these actually are in operation for large scale electricity storage today: pumped hydro storage and CAES. Storage technologies may be seen as competitors to load control of production units and demand response by consumers.

4.2.7 Electricity storage in the energy system

The CAES plant in Huntorf, Germany, is equipped with a 60 MW compressor unit, a 290 MW turbine unit and 300.000 m³ cavern for storage of 500 MW compressor input power. It has had 30 years of operation as an integrated part of the electric system of Northern Germany. The construction of the plant was decided to make it possible for a nuclear power station to operate at full load while the consumption fluctuated. Due to less and less operation of the nuclear power stations the number of operating hours of the Huntorf plant was decreasing. However, over the last decade the number of operating hours has been increasing due to installation of more fluctuating production units, i.e., wind turbines. The example shows that a properly working electricity storage unit may be an important part of the electricity system. As fluctuating production units receive increasing focus and are installed to large extent globally there may exist significant potential for electricity storage in the future energy system.

In order to install storage units we will have to accept :

- Losses in the electricity-to-storage-to-electricity cycle
- Addition of investments and operating and maintenance costs to the resulting electricity price

Further investigation of the CAES technology reveals all of these issues: CAES involves losses in the compression process as well as the turbine. Most losses occur due to intercooling of the compressor which is required as the underground salt caverns do not tolerate high temperature. As a consequence, the turbine expansion requires heating by natural gas combustion to avoid extremely low temperatures during expansion. Thus, we see that the material limits of the storage will result in significant requirements for design of the process and that these result in both high investments in equipment and storage and in operating costs for fuel.

Suggestions for improvement of the process show that storage of energy at high temperature or increasing the number of compression steps may improve efficiency and lower the fuel consumption significantly. However, such improvements will require research and development, e.g. within thermodynamics to optimize the process, within fluid mechanics to develop turbomachinery, within material science to develop high temperature storage systems.

By this example it can be seen that even mature technology needs scientific work at several levels. The same is the case for other technologies, which are less mature. Different technologies utilize electricity storage by conversion to other energy forms and thus require investigations within several fields of science in order to make a highly efficient electricity storage economically feasible.

4.2.8 Energy efficiency by storage

The range of options shows that many different technologies may be involved and that many different systems may be proposed. It has been observed that each step of the full conversion from electricity to storage and back to electricity introduces a loss of electric potential (exergy). This means that any electricity storage will result in losses. It will thus introduce an extra cost of the output electricity from the storage compared to the production cost.

In addition to the efficiency of the storage, several other factors are of importance in the design of a large-scale electric storage, e.g. volume density, mass density, cost, geographical requirements, start up time and impacts on the overall energy system. One important observation is that storage of large amounts of energy requires a lot of space when the full storage cycle is taken into account.

Many different fields of expertise and research will be involved in developing an optimum system for storage of electricity. The current interest in it opens up many possibilities for R&D and for interaction between different types of research, such as materials science, fluid mechanics, electric engineering, thermodynamics, geology, civil engineering and chemical engineering.

4.2.9 Heat pumps

Heat pumps are in general a mature technology which is available for heating of residential buildings and industrial installations. In a heat pump the surroundings are cooled by a refrigerant. By addition of external energy resulting in an increase of pressure, the temperature of the refrigerant is increased. This makes it available as a heat source. The external energy may be delivered as mechanical power for driving a compressor (compression heat pump) or as high temperature heat, e.g. steam or waste heat, for driving an absorption system. The effectiveness of a heat pump is usually determined by the Coefficient of performance (COP) which measures the total energy available for heating compared to the input of driving energy. The COP values of heat pumps driven by mechanical compression and that by absorption are not comparable.

4.2.10 Compression heat pumps

Most heat pumps are running by the compression cycle utilizing electricity to transfer the external heat source at low temperature to a temperature high enough for heating purposes. These may be integrated with solar heating systems to raise the low temperature in the system as this will improve the COP. Mechanical heat pumps will improve the energy economy of electrical heating at the cost of installation of a heating system in the building. Compared to domestic boilers based on oil or natural gas the primary energy efficiency is of the same order as heat pumps consume electricity that is usually produced at an efficiency of the order of 30-45% at a thermal power station. The heat pump converts electricity to heat by a COP factor of the order of 3-4. If electricity is produced by other sources more sophisticated comparisons are required.

4.2.11 Absorption heat pumps

Absorption heat pumps are used in the Copenhagen area in connection to the district heating system of the city. The plant uses geothermal energy as low temperature heat source and extraction steam from the Amagerværket power station as driving heat for the absorber. Absorption systems usually require big investments and the availability of a high temperature waste heat for driving.

4.2.12 Research and development

A significant amount of research is done in order to improve both types of heat pumps. The research aims at improvement of:

- Operating fluids: natural refrigerants for mechanical heat pumps, in particular CO_2. For both types of heat pump fluids for operation at higher temperature in district heating are of interest
- Cycle improvement of both types of cycles
- Integration with other systems such as solar heating or biomass
- Integration in combined heat and power system

Integration in electric systems with large shares of wind power and CHP is an interesting application of heat pumps as it opens the opportunity for additional utilization of fluctuating electricity production. This may be used for driving heat pumps and can thus make it possible to have renewable energy in the district heating system. Several Danish companies have investigated this possibility and developed technical solutions for it. The research is aimed at selection of operating fluids and development of compressors for high temperature applications as well as improvement of system COP. The COP that can be obtained will be relatively low due to the requirement of a large temperature difference between low temperature heat source and the high temperature forward in the district heating system.

4.3 Energy savings and efficiency improvements

4.3.1 End use energy efficiency improvements

"Negajoules" (energy consumption avoided through savings) have become the single most important "energy resource" in the EU. Even though energy efficiency has improved considerably during the last decades, it is technically and economically feasible to save even more energy. This potential plays a prominent role in the European Energy Action Plan adopted in March 2007 by the European Council [11]. As part of this plan, the EU leaders set the objective of saving 20% of the EU's energy consumption compared to current projections for 2020.

Realising this potential, which is equivalent to some 390 Mtoe in the year 2020, will yield large energy and environmental benefits. CO_2 emissions should be reduced by 780 million tCO_2 for the single year 2020 with respect to the baseline scenario – more than twice the EU reduction required under the Kyoto Protocol for the whole 5-year period 2008-2012. Additional investment in more efficient and innovative technologies will be more than compensated by annual savings exceeding €100 billion by 2020.

The further down the chain efficiency is improved, the greater the impact on primary energy consumption and emissions. As an example based on data from 2002 averaged across the EU, 1 kWh of electricity at the point of use requires 2.2 kWh of energy from primary fuel to be converted in a power plant accompanied by the emission of about 314 g of CO_2. Including the energy used upstream of the power plant – to extract, process and transport the primary fuel – multiplies the primary energy consumption and CO_2 emissions by a further factor of 1.08, so every kWh saved at the point of use means a saving of around 2.4 kWh in primary energy and 340 g of CO_2.

Energy conversion losses account for 33% of the primary energy consumption in the EU. These losses can be cut significantly by introducing combined heat and power (CHP) generation. To date, only around 13% of all electricity in the EU is generated using this technology, and it is recommended to increase this fraction to approach the Danish figure of 50% electricity production by CHP, always under the precondition that the thermal waste energy from the cogeneration process is used adequately for heat applications.

According to the IEA approximately one-third of end-use energy consumption in IEA member countries occurs in residential, commercial and public buildings. Uses include heating, cooling, lighting, appliances, and general services. Buildings are therefore a major demand on energy resources and the emissions associated with supplying and consuming this energy make up an important component of total emissions. Using an accounting system that attributes CO_2 emissions to electricity supply rather than building end-uses, the direct energy-related carbon dioxide emissions of the building sector are about 3 Gt/yr. Savings in residential and commercial buildings, transport and manufacturing have energy saving potentials of 25-30%. Buildings account for about 40% of the total final energy consumption in the EU. Most of the energy used in buildings takes the form of low-temperature heating for rooms and domestic hot water. Electricity, which is a high-grade form of energy, is also used in large quantities for building services such as lighting, air conditioning and ventilation, as well as for the electrical equipment used in homes, shops and offices.

The largest savings potential in end-use energy is in buildings, in particular retrofitting of old buildings. It is highly recommended that the principles of the European Energy Performance of Buildings Directive (EPBD) are followed everywhere for both new and existing buildings. By doing so in all EU countries, it is estimated that 28% energy savings in this sector can be achieved by the year 2020 corresponding to a reduction of the total EU final energy consumption by 11%.

Electricity is a "high-quality" (high-exergy) form of energy that should preferably be used for applications such as lighting, electronic equipment and motorised appliances, for which other forms of energy cannot be used. Electricity for space heating makes sense in the case of low energy houses, where the thermal time constants of conventional hydraulic systems lead to overheating of rooms, or by using very efficient heating technology such as heat pumps.

Energy sources suitable for heating buildings include solar thermal systems, heat pumps, waste incinerators and CHP systems. District heating systems, in which heat produced in one place is used elsewhere, can improve energy efficiency through economies of scale and by providing heat storage to smooth out variations in heat supply and demand. Individual heat pumps and solar heating systems can supply heat to buildings in the countryside and other areas where district heating is not available. Individual solar photovoltaic (PV) systems and wind turbines can also provide electricity, making buildings entirely sustainable and self-sufficient, though using wind power to run heat pumps can be problematic on calm winter days.

There are important niches for Danish R&D in monitoring and reducing the electricity consumption of private households. Examples are methods of visualising the standby power consumption of equipment, energy-efficient lighting technology such as LEDs, energy-efficient hot water circulation pumps for one-family houses, and integrated heating systems – heat pumps, solar cells and ventilation – for houses and holiday homes. The EU commission prepares a plan for progressive phasing out incandescent bulbs starting in 2009.

4.3.2 Energy efficiency in transport

Special attention should be paid to transport. World energy demand for transport has increased significantly for many years. This trend is projected to continue in the years to come, one reason being that large and rapidly developing economies have increasing demand for the transport of both goods and people, including rising transport demand due to greater integration of developing countries in international trade.

Transport not only accounts for approximately 20% of the total world energy consumption, but is almost entirely based on fossil energy resources and thus is a major contributor to the CO_2 emissions. This has put huge political emphasis on sustainable alternatives to fossil fuels for transport; the trend in European transport policy is to encourage reduction of fossil fuel use.

The car industry continues to improve the fuel efficiency of conventional vehicles by reducing weight. In the power train this is done by replacing cast iron with lighter alloys based on magnesium and especially aluminium, while bodywork and structural elements are lightened by using polymers and composites instead of steel. These efforts are strongly supported by the EU, and in principle they will cut CO_2 emissions.

The internal combustion engine in a hybrid car is small compared to that in an ordinary car, because at times of peak power demand it is backed up by the electric motor. In addition, energy use is controlled more carefully than in a conventional vehicle, and energy released during braking is used to charge the battery so that it can be re-used during acceleration. Taken together, these techniques result in fuel consumption much lower than in today's standard cars.

Table 4
Energy technologies, future challenges and possibilities

Technology	Technological status	Commercial contribution	Annual average growth [1]	Major challenge	Major barrier	Cost per ton CO_2 reduction, USD/tCO_2-eq [2]
Wind	Mature	Exists	17.1%	Integration of high shares in the grid	Insufficient international standards	< 0 - 50
Photovoltaics	1G: Mature 2G: Market penetrating phase 3G: Research phase	2016	40%	Cost reduction and increased lifetime for 2nd and 3rd generation solar cells. Advanced manufacturing techniques	Lack of feed-in tariff and other incentives (except for Germany)	50 – > 100
Solar thermal	Mature	Exists	17 – 20%	Connection of solar thermal to district heating network		
Biomass based fuels for transport	1G bioethanol: Mature 2G bioethanol: Demonstration phase GTL-technology: Mature in niche areas	1G: Exists 2G: 2010	6.3%	2G: reduce energy demand, operating costs and capital costs in integrated biorefinery demonstrations	Bioethanol: Disparity in custom duties and, tax exemptions; GTL-technology: Motors and distribution systems	< 0 – 100
Thermal fuel conversion technologies - biomass	Mature (large potential for optimization)	Exists		To obtain high power efficiency and fast load adaption	Insufficient knowledge of the real potential	
Thermal fuel conversion technologies	Coal: Mature	Coal: Exists	Coal: 1.8% Gas: 2.3% Oil: 1.3%	Shift toward low- and zero-carbon sources, capture and store the CO_2 emissions	Coal: Price stability and abundance	
Nuclear energy	Mature	Exists	0.7%	Uprating and life extension	Costs, safety, waste management, and proliferation risks	< 0 – 20
Fusion energy	Research phase	2045		Make ITER a success	immense investments in R&D are needed	Not available
Geothermal energy	Mature	Exists	20%	Exploitation of the resources at greater depths	Build the necessary infrastructure	< 0 to 50
Hydro, ocean, wave and tidal	Hydro power: Mature Wave, current and tidal: Demonstration phase	Hydro: Exists Wave, current and tidal: 2020	2%	Hydro: None Wave, current and tidal: Reliability and cost	Hydro: resources and planning Ocean, wave and tidal: regulatory barriers	Hydro: < 0 to 50 Wave etc: Not available
Fuel cells	SOFC: Market entering phase in niche markets PEMFC: Commercial in niche markets	SOFC: 2010 PEMFC: Exists		SOFC: Lower working temperature	SOFC: Lack of testing and demonstration	Not available
Hydrogen	Research phase; Demonstration phase in some projects	2030		Sustainable production of hydrogen	Storing and infrastructure	Not available
CCS	Research and demonstration phase	2015		Reduce the "energy penalty" with around 25%	Full scale demonstration of the technology	CCS + coal: 20 – 50 CCS + gas: 20 – 100
Storing technologies	Pumped hydro and CAES: Mature Other: Research, development or demonstration	Exists		Costs		
Heat pumps	Mature for domestic applications Research phase for district heating integration	Exists		Investments		
End use energy efficiency improvements	Mature	Exists		Reverse consumer behavior	Lack of efficient dynamic standards, reliable labelling, white certificates and behavioural research	> 0 - 20 [6]

Notes: [1]: Figures form Risø Energy Report 6 [1] and WEO 2006 [8] (or later if available)
[2]: Figures from IPCC WG III AR4 (2007) [9]
[3]: Figures from IPCC WG III AR4 (2007) [9]

Mitigation potential GtCO2/yr [3]	Needed research and development	Danish strengths	Total share of global energy mix 2007 [4]	Potential total share of global energy mix 2030 [5]	Possible adverse effects
3.1	Improved performance and reliability through advanced rotor technologies and power train enhancements and generic long-term research	World leading in research, development and production	3.3% of electricity	29.1% of electricity	Visual intrusion and environmental considerations for land based turbines Disposal of worn out turbines
0.25	Efficiency improvement and prolonged lifetime for polymer and nanomaterial solar cells	World leading in polymer solar cell research	0.1% of total supply	1 – 2% of electricity	Harmful production materials, disposal measures and land use in some areas
1.22	Bioethanol: Pretreatment, C5 fermentation integration GTL: Integration of the GTL technology with power production	Bioethanol: Efficient enzyme systems, pretreatment processes for 2G	1% of transport fuel	10% of transport fuel	Consequences of using the land to produce fuel rather than food. Consequences of competing uses of land.
	large biomass fuel share on power plant boilers, increased electrical efficiency of waste combustion plants, development of mature and flexible pressurized gasification technologies, development of reliable biomass pyrolysis reactors	Biomass combustion research conducted in collaboration between industry and universities		25%	Consequences of using the land to produce fuel rather than food. Consequences of competing uses of land.
	Economic acceptable high efficiency combustion technologies, clean utilization technologies and CCS		Coal: 25% Gas: 25% of electricity Oil: 37%	Coal: 25% Gas: 31% of electricity	Emissions of CO_2, NOx and SOx
1.88	Development of Generation III+ and Generation IV fast neutron reactors with efficient closed fuel cycle	None	16% of electricity	10% of electricity	Waste management, disposal and proliferation
Not available	Understanding and control of the plasma	Modeling of turbulence and transport in plasmas	0		Worn-out reactors will be radioactive for 50 – 100 years, but there is no long-lived radioactive waste
0.43	Further development of the hot dry rock technology	Utilization of the results from the demonstration plant at Amagerværket	0.4% of total supply	2% of total energy mix	Risk of CO_2 releases from the underground during the heat extraction
Hydro: 0.87 Wave etc: Not available	Hydro: None Wave etc: Large demonstration projects. Computational modelling and evaluation of innovative concepts	Hydro: None Wave: Promising demonstration projects, e.g. Wave Dragon and Wave Star	Hydro: 16% of electricity Wave, current and tidal: 0	Hydro: 16% of electricity Wave: 10% of electricity	Hydro: Environment, resettlement, lack of sites Ocean, wave and tidal: Environmental sensitivities
Not available	SOFC: Lower working temperature, lower production costs and stacking	SOFC: Among the world leaders and close cooperation with industry, e.g. Topsoe Fuel Cell A/S			Disposal of worn out fuel cells
Not available	Development of cost effective storage and sustainable production technologies	SOEC electrolysis cells; Demonstration projects			Atmospheric and environmental risks and safety
CSS + coal: 0.49 CSS + gas: 0.22	Development of systems with lower costs of CO_2 capture	Research in capture and pre-combustion capture; Experience from the demonstration plant in Esbjerg			Leakage of captured CO_2 to the atmosphere; Sudden release could be dangerous to the health
	Improvement of efficiency of existing technology and development other types for high efficiency	Possible integration with wind power			Geographical and geological requirements
	High temperature systems for CHP integration and for absorption systems in waste heat recovery	Extensive CHP system			
5.0	Consumer behavior	Low energy buildings; Passive houses; LED lighting			

Notes: [4] : Figures from WEO 2006 [8] and Risø Energy Report 6 [1]
[5] : Figures from WEO 2006 [8] and Risø Energy Report 6 [1]
[6] : IPCC WG III AR4, p 389 [9]

System aspects

5

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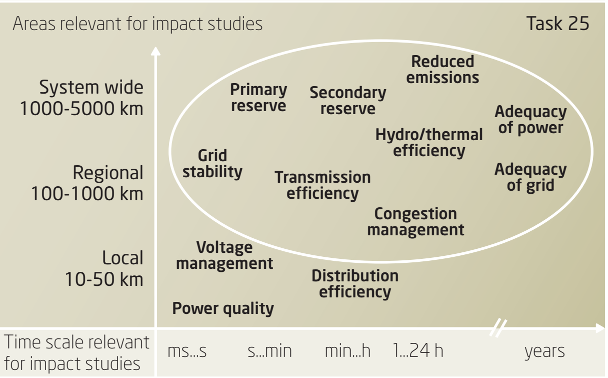
An energy system with large-scale integration of renewable energy, particularly wind power, is expected to meet the same requirements for security of supply and economic efficiency as the energy systems of today, while delivering better environmental performance, especially with regard to CO_2 emissions and dependence on fossil fuels.

Wind power affects power systems at different scales of time and geography (Figure 6), starting with local issues of grid connection (power quality), and going all the way up to system-wide effects (reliability and adequacy).

Figure 6
Effects of wind power on power systems at different scales of time and geography [1]



Large proportions of wind power and other fluctuating renewable generation technologies introduce uncertainty into the power system. In such cases the system's flexibility in generation, demand management and intra-area transmission may therefore need to be increased. The layout and basic structure of the grid, as well as operational practices, need to adapt to the presence of large amounts of fluctuating supply.

There are four main areas of interest: renewable energy power plant capabilities; grid planning and operation; energy and power management; and energy markets. Each of these is important for the large-scale integration of wind power at a system level. This chapter describes the system aspects involved in using wind power at high levels of penetration.

5.1 Renewable energy power plant capabilities

5.1.1 Power control

To obtain the maximum benefit from a power system as a whole, large-scale renewable energy should replace energy from conventional thermal power plants; this way both consumption of fossil fuels and the resulting emissions can be reduced.

Some of today's large wind farms already have some of the main characteristics of conventional power plants. One of these is the ability to control the amount and quality of the power produced. Modern wind turbine technologies make it possible to control both active and reactive power, though the power a wind plant can produce at a given time is obviously limited by the strength of the wind.

Since the wind itself costs nothing, reducing the power produced by a wind farm below the maximum power available in the wind at that time reduces operating costs by only a very small amount. Still, such reduced production can be required in critical system situations when other control reserves are scarce, and it can be a low-cost option during periods where the market price of electricity is low or zero.

In Denmark, low to zero electricity prices sometimes occur during cold and windy periods. At such times, combined heat and power (CHP) plants need to increase production of heat for buildings, leading to the generation of large amounts of CHP electricity when the output from wind turbines is also high.

5.1.2 Fault ride-through

The behaviour under grid fault conditions (fault ride-through capability) of renewable energy generation is a key issue in the large-scale use of renewables in a power system. This is reflected in the grid codes – the rules that govern the behaviour of generating equipment, including grid-connected wind turbines – now used by every country planning to develop large-scale wind power.

The purpose of fault ride-through is to ensure that the renewable generation is able to stay connected to the grid during and after a grid fault. Today, most wind turbine manufacturers provide wind turbines with fault ride-through capabilities. If the turbines are not able to stay connected during and after the fault, the consequence is a sudden loss of generation which must be replaced by fast reserves from other generators to prevent loss of load. Fault ride-through is not unique to renewable generators; similar capabilities are required of conventional generators to ensure that the system will continue to operate if one generating unit fails.

5.1.3 Black start and isolated operation

Another fault mode arises when part of the grid becomes isolated from the main synchronous system. If the isolated area is able to control its own frequency and voltage, a blackout can be avoided and the reliability of the power system improves. If the part of the system that is isolated is dominated by renewable and decentralised generation, then the contribution of these generators to the control of frequency and voltage can be the key to avoiding substantial load shedding or even a blackout.

If a blackout cannot be avoided, it is important to re-start the system as soon as possible afterwards. This "black start" process can be supported by renewable and distributed generation, provided that these generators support frequency and voltage control. In cases like these, the control dynamics of the power system can be very important. Risø DTU has run a number of simulations of wind farm models connected to simplified grid models, to test the ability of wind farm power controllers to provide the necessary grid support [2].

5.1.4 Reliability

The reliability of wind power is an issue in normal operation as well as under fault conditions. Wind farm owners measure reliability in terms of their ability to sell power. In this case, a simple measure of reliability is the ratio of actual production to the energy available according to wind speed data and turbine power curves, taking into account failures in wind turbines and the grid itself.

From the point of view of the system operator, reliability is mainly about the risk that all or some of the predicted wind power will not be produced. Factors affecting this measure of reliability are:

- Power forecasting errors caused by errors in wind speed forecasts; these generally cannot be avoided, but can probably be reduced
- If the wind speed rises to the "cut-out" speed of the turbines, production of individual turbine drops suddenly from rated power to zero
- Failures in the transmission line linking the wind farm to the transmission system
- Failures in the power collection grid within the wind farm
- Failures of wind turbines

At the power system level, reliability is about the total performance of all the wind farms in the system, not about failures of individual turbines or wind farms.

Another reliability issue is whether the power system can handle peak loads. With large-scale renewable generation in the system, many thermal power plants will have to operate at reduced load factors. This may reduce investment in new thermal power plants, which in turn might lead to problems with system adequacy at peak loads when the amount of renewable generation is low.

A major research challenge is to build reliability models that combine general reliability factors, such as grid failures, with factors specific to wind power, such as wind forecast errors and cut-outs at high wind speeds.

5.2 Grid planning and development

One of the biggest challenges to the reliable integration of large amounts of wind energy in power systems is power transmission. Areas with good wind potential are often located far from load centres. To manage variable energy production on a large geographic scale, the grid infrastructure and interconnections should be extended and reinforced. As the first phase of the European Wind Integration Study (EWIS) [1] concluded, without grid reinforcement Europe will not be able to reach its targets for renewable energy [3].

Large-scale integration of renewable energy requires a pan-European transmission network for effective cross-border power trading and mutual support for security and quality of supply. There is a need for advanced simulation and analysis tools, combined with dynamic calculations for the interconnected European power system. Planning tools should be developed for the design of efficient grids.

Risø DTU is taking part in several projects aiming to develop software tools and use them for grid integration studies. One of these is TradeWind [4], an EU-funded project which aims to provide technical and economic justification for strategic decision-making on the development of the EU's grid and generation infrastructure [4].

[1] An initiative established by the TSO associations of the European transmission system operators (such as UCTE and ETSO) in collaboration with the European Commission.

In addition to grid planning and development, better and more reliable use of the existing grid is required. At the distribution level, new system architectures and operating modes – notably demand response – are being investigated.

5.3 Energy and power management

In any power system, the instantaneous power production must be maintained in perfect balance with power consumption at all times. Transmission system operators (TSOs) use different types of reserves to maintain this power balance. The Nordel market area comprises the AC-connected synchronous Nordic system (Norway, Sweden, Finland and East Denmark) and West Denmark, which is connected to the synchronous Nordic system via high voltage direct current (HVDC) links.

Reserves are activated whenever planned production and expected consumption deviate from actual production and consumption. The system operates as a cascade. As soon as there is a power imbalance, the frequency changes and the primary reserve reacts automatically and very rapidly to counteract this. The technology is known as Automatic Generation Control (AGC).

Next, the secondary reserve is activated manually by the TSOs, taking the cheapest bids first from the common balancing market of Nordel TSOs. Activation of the secondary reserve relieves the primary reserve, which it is then free to handle new deviations.

Deviations between power production and consumption have three main causes: errors in forecasting consumption, fluctuating production, and outages of power plants or transmission lines. In the Nordic system, producers and consumers sell and buy electricity on the day-ahead Nord Pool market: obligations to produce or consume power are fixed 12–36 hours before the power is actually delivered or consumed. Wind power producers base their day-ahead sales on wind forecasts for the corresponding period, and these are less reliable than the forecasts of electricity consumption relied on by buyers. As the amount of wind power in the system increases, power balance predictions therefore become dominated by the error in predicting wind power production.

The necessary allocations of both primary and secondary reserves are determined by the N-1 criterion – the amount of reserve needed to cover the loss of the largest generating unit in the whole Nordel system (for primary reserves) or the region covered by each TSO (for secondary reserves). In addition, a normal operational primary reserve is held in the Nordel area and bids from the common balancing market are used as secondary reserve.

As the amount of wind power increases, the wind power forecast error starts to increase the required amount of reserves, especially secondary reserves.

There are several ways to add the necessary extra control capacity to the system. One interesting possibility is the addition of electrically-driven heat pumps to Danish district heating systems. This could provide price-flexible power management, with the heat pumps consuming power whenever it is cheap, and shutting down temporarily when reserve power is needed. Other forms of flexible power consumption such as plug-in hybrid vehicles might also become attractive within the next ten years.

Power control of wind turbines is a less obvious way to correct imbalance between supply and demand, because, unlike with a conventional generating plant, down-regulated wind power is lost forever. However, the Danish grid codes require large wind farms and new large wind turbines to have active power control. The two largest wind farms in Denmark, Horns Rev (160 MW) and Nysted (165 MW), both have controllers that support active power control. The wind farm controllers are used by the TSOs to maintain stability in critical situations, while power producers who own both wind farms and conventional power plants take advantage of the rapid controllability of wind power to balance the much more sluggish response of conventional plants.

5.4 Energy markets

Power is traditionally traded in a series of forward markets (day-ahead markets or bilateral contracts), so the amount of power to be produced and consumed within any given hour needs to be determined beforehand. In the case of Denmark, for instance, the Nordic power pool's day-ahead market (Nord Pool Spot) operates 12-36 hours in advance.

A higher proportion of power that is only partly predictable, such as wind power, creates more deviations between the production planned in the markets and the actual power produced during the hour in question. Making up any shortfall requires calling on short-term regulating power, which is more expensive than power bought in the day-ahead market. The extra costs of using regulating power are paid either by the producers or by the consumers, according to specific "imbalance settlement" rules set by the market. Whoever pays, it is important to ensure that the amount accurately reflects the cost of keeping the system in balance. A wind power producer, for instance, should not have to pay more than the actual costs incurred by wind power prediction errors [5]. Risø coordinated WILMAR, an EU-funded research project that developed a planning tool for analysing the operational consequences of wind power prediction errors (www.wilmar.risoe.dk). The WILMAR planning tool has been used for wind integration studies in Ireland, and is presently used in phase two of the EWIS study mentioned above.

The shorter the timescale at which the power market can function, the more accurate the wind power forecasts will be. It will therefore become increasingly important to create intra-day markets that can trade closer to the actual delivery. A requirement for well-functioning intra-day markets should be for all power producers to make their regulating capabilities available for the intra-day as well as for the regulating power markets. The use of flexible power consumption (demand management) in the regulating power market can decrease regulation costs, so the development of market-based solutions to allow this should be continued.

Regional developments in energy systems, economics and climate

6

6.1 OECD countries

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The countries of the OECD[2] strongly influence the development of energy demand and new energy supply opportunities. OECD members are generally characterised as well-developed, industrialised countries, the only exceptions being Mexico and Turkey. In the development of new renewable technologies such as photovoltaics, wind power and biofuels, the OECD countries are amongst the fastest, as shown by examples such as wind power in the EU and North America, and photovoltaics in Germany, the USA and Japan. This section outlines current trends in the development of energy demand and supply in the OECD countries, including the main economic and demographic drivers and policy initiatives.

6.1.1 Economic and demographic development

Among the drivers for energy development, two of the most basic are economic growth and population growth. By 2004 the total population of the OECD nations was close to 1,200 million, or approximately 19% of the global population. For comparison, India and China have around 16% and 20%, respectively, of the world's population. The population of the OECD countries has grown only modestly for many years, however, while over the last 25 years India and China have seen average annual population growth of 1.5% and 1.2% respectively (Table 5).

By 2005 the OECD's share of global gross domestic product (GDP) was 77%, while India and China had approximately 5% and 2%, respectively[3]. Thus, although the populations of these three blocs are very similar, there is still a big difference in the value of the products they manufacture, with the OECD having almost 15 times the GDP of China.

As with population growth, however, economic growth in the OECD countries has been moderate: around 2.8% annually on average from 1980 to 2004. In comparison, annual growth in India and China has been much faster, averaging almost 6% for India and almost 10% for China in the same period. Moreover, the growth rates of the mature industrialised OECD countries are declining, while India and China – if we discount a few ups and downs of the world trade cycle – have maintained their high average growth rates for more than 20 years. Table 1 shows the growth in population and GDP for selected economic groupings and countries.

Figure 7 shows GDP (2007) per capita for selected countries and regions. The chart clearly shows the difference in economic terms between the industrialised western countries and the developing countries such as India and China, per-capita GDP for the USA being 20 times than of China and 45 times that of India. These gaps are narrowing rapidly, however: in 2000 the USA had 33 times the per-capita GDP of China, so a corresponding figure of 20 in 2007 represents a catching-up by nearly 40% in seven years.

6.1.2 Energy development

In 2005, total primary energy demand in the OECD countries was 5,542 Mtoe, or almost 49% of the global energy demand. The USA was the world's main energy consumer, accounting for 20% of total demand; China's share was 15%,

Table 5
Growth rates of population and GDP for selected economic groupings and countries

	Population growth % /y		Economic growth % /y	
	1980-1990	1990-2004	1980-1990	1990-2004
OECD	0.8	0.8	3.0	2.5
USA	0.9	1.2	3.2	3.0
EU	0.3	0.3	2.4	2.1
Japan	0.6	0.2	3.9	1.3
Transition economies	0.6	-0.2	-0.5	-0.8
Developing countries	2.1	1.7	3.9	5.7
China	1.5	1.0	9.1	10.1
India	2.1	1.7	6.0	5.7
Brazil	2.1	1.5	1.5	2.6
World	1.7	1.4	2.9	3.4

[2] Organisation for Economic Co-operation and Development. The OECD region comprises the EU member states, the USA, Canada, Japan, Australia, New Zealand, South Korea, Iceland, Norway, Turkey and Mexico.

[3] Calculated in constant USD at the 1995 exchange rate.

Figure 7
GDP (USD) per capita for selected countries and regions, 2007

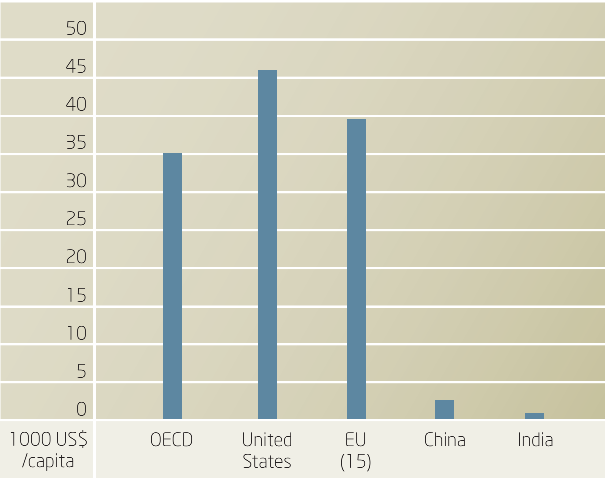
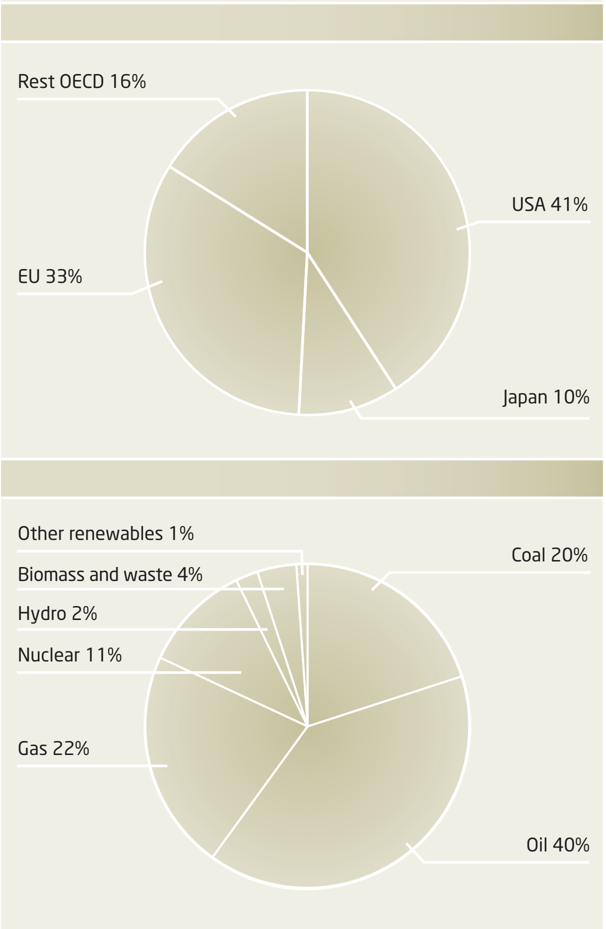


Figure 8
Primary energy demand in the OECD by country and fuel type, 2005



and India's just 5%. The OECD share of the world's energy use has gradually declined from 52% in 1990 to 49% in 2005. In the same period China has increased its share from 10% to 15%.

By 2005 primary energy demand in the OECD region was dominated by the USA and the EU, with 41% and 33%, respectively, of the OECD total (Figure 8). Third was Japan, with approximately 10%. Over the last 15 years OECD's primary energy demand has grown at an average annual rate of 1.4%, but with a tendency towards slower growth in recent years. Thus the growth of primary energy demand in the OECD is fairly slow compared to China (4.7% in the same period) and India (3.5%).

Oil is still the dominant fuel, accounting for 40% of OECD primary energy, followed by gas (22%) and coal (20%). Renewable sources, including hydro, biomass and waste, covered approximately 7% of OECD total primary energy demand by 2005.

In 1990, for comparison, the relative contributions of oil and coal were higher (41% and 24% respectively), while that of natural gas was lower (19%). However, although the proportion of oil fell between 1990 and 2005, total oil consumption rose by 1.2% /y in the same period. Consumption of coal increased modestly, by 0.4% annually, while consumption of natural gas increased by 2.4% annually.

Total final energy consumption in the OECD can be split into three sectors of almost equal size: industry (30%); transport (34%); residential, services and agriculture (33%)[4]. Industrial use of energy has grown only moderately in the last 15 years (0.8% /y), Residential, services and agriculture has grown by 1.4% /y, and transport has grown the most significantly, by 1.8% /y. Energy use for power generation and heating plants has increased by 1.7% /y, and now accounts for almost 40% of primary energy demand in OECD countries.

Mainly because of its rapidly growing transport sector and shrinking domestic supplies of oil and gas, the OECD as a whole is becoming increasingly dependent on imported fossil fuels. Oil production in OECD countries peaked at the beginning of the current decade and is now gradually falling, especially in Europe, but to a lesser extent also in North America. Figure 9 shows OECD dependence on imported oil and gas. The decline in domestic oil production implies that by 2005 the OECD was importing 57% of its oil needs, and this figure is expected to increase in the future. OECD

[4] The remainder is for non-energy use.

Figure 9
OECD imports and exports of oil and gas, 2004
(note the different scales of the axes)

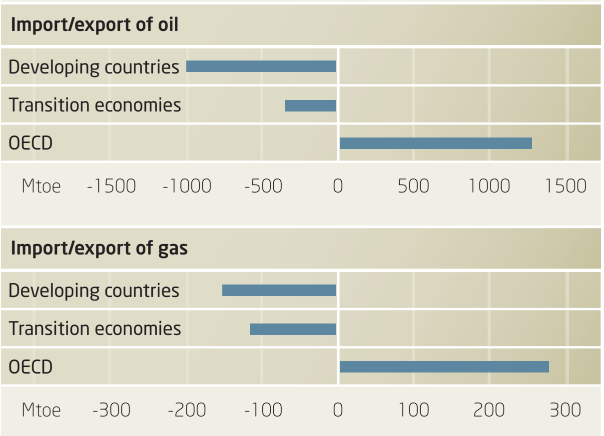
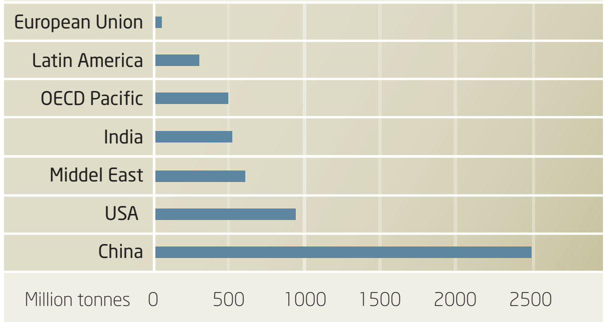


Figure 10
Increase in energy-related CO_2 emissions from selected countries and economic groupings, 1990-2004



gas imports are relatively lower, at 23% of consumption, but are also expected to rise.

Fossil fuels thus still heavily dominate the OECD's energy supply, and this is clearly reflected in emissions of CO_2. By 2005, CO_2 emissions from OECD countries totalled 12,838 Mt, or 48% of the world total. The main OECD contributor is the USA, whose CO_2 emissions account for 22% of the world total, followed by the EU (15%) and Japan (5%)[5]. In comparison China in 2005 emitted 19% of global CO_2 emissions, and India a little more than 4%. Thus China and the USA now have almost the same energy consumption and CO_2 emissions, although the USA has a GDP more than five times that of China[6].

In the last 15 years CO_2 emissions from the OECD as a whole have increased by 1% annually. In the USA emissions have grown faster, at 1.2%, while for Japan the figure is 0.9%, and in the EU CO_2 emissions have been declining by 0.2% annually. Both China and India doubled their CO_2 emissions from 1990 to 2005, corresponding to annual growth of approximately 5%. Figure 10 shows the increase in CO_2 emissions by country and economic grouping for the period 1990-2004. The influence of China and the USA is overwhelming: China by itself accounted for 44% and the USA for 17% of the total rise in CO_2 emissions during this period.

Despite efforts to curb greenhouse gas emissions, the situation is getting worse. From 1990 to 2000, the average annual global increase in emissions was 1.1%. Between 2000 and 2005, though, growth accelerated to 2.9% per year, despite the increased focus on climate change. High economic growth, notably in coal-based economies, and higher oil and gas prices (which have led to an increase in coal-fired power generation) are the main reasons for the increase. Emissions from coal use increased by 1% per year between 1990 and 2000, but by 4.4% per year between 2000 and 2005.

6.1.3 Trends in renewable energy

On the world scale, renewable energy is still dominated by the "old" renewables, hydropower and traditional biomass, which supply respectively 6% and 9% of global primary energy demand. In 2004 renewable sources supplied approximately 17% of global primary energy demand. Subtracting the contributions from hydro and traditional biomass leaves only around 2% attributable to "new" renewable sources such as photovoltaics (PV), wind power, small scale hydro, biogas and new biomass.

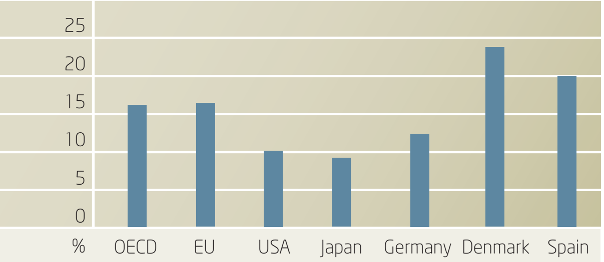
Nevertheless, while the two "old" renewables are increasing only slowly or even staying constant in absolute terms, the contributions from new renewable sources are expanding rapidly. Today the fastest-growing energy technology is PV, which over the last five years has increased at 35% per year. Other new renewables are not far behind: over the same period wind power has grown by 28%, biodiesel by 25% and solar water heating by 17%, all calculated as average annual growth rates [2].

Compared to the rest of the world the OECD has a significant share of renewable energy, especially in "new" renewables, and OECD countries including Germany, Spain, the USA, Japan and Denmark have seen remarkably rapid development. Figure 11 shows the use of renewable energy sources in power generation in selected countries and economic groupings.

[5] The shares of total OECD CO2 emissions for the USA, EU and Japan are 45%, 31% and 9%, respectively.

[6] 2006 calculated in constant 1995 USD.

Figure 11
The contribution of renewable energy sources in power generation, 2006



Source: Enerdata [1]

Some OECD countries are also among the most active in adopting new policies to promote renewable energy.

By 2007 the EU member states, for instance, had adopted a long-term target for renewable energy: by 2020, the plan is that 20% of the EU's final energy demand will come from renewable technologies such as wind, solar and biomass. This target will be implemented mainly through national initiatives[7], and at the start of 2008 the European Commission presented a proposal for sharing the burden among the EU member states. The proposed share of renewables by 2020 varies significantly between member states: Denmark, for instance, is set for an increase of 13%, to a total of 30% renewable energy, while the Czech Republic will see an increase of 6.9%, to a total of 13%. While this division is still being negotiated, there is no doubt that the EU's binding targets will create strong incentives for the continued rapid development of renewable energy technologies in Europe.

At present the use of wind power is soaring in the USA, driven mainly by federal tax credits (the Production Tax Credit, or PTC), but biofuels are also developing rapidly. With the exception of California, individual states provide relatively little R&D support for renewable technologies. However, more and more policy initiatives supporting the deployment of renewables are being taken at state level, including quotas for renewables (Renewable Portfolio Standards).

6.1.4 Conclusions

The OECD countries are amongst the most active in adopting new policy measures to reduce greenhouse gas emissions and support the development of energy-efficient and renewable energy sources. At the same time these countries are becoming increasingly dependent on imported fossil fuels, mainly owing to a rapidly growing transport sector and shrinking domestic supplies of oil and gas.

By 2005 40% of the OECD's energy demand was still met by oil, of which 57% was imported – and this share is expected to rise in the future. Natural gas provided 22% of the OECD's primary energy in 2005. Only 23% of this gas was imported, but this proportion is also expected to rise.

This dominance of fossil fuels in the energy supply of the OECD countries is clearly reflected in CO_2 emissions. By 2005, OECD CO_2 emissions amounted to 12,838 Mt, or 48% of the world total. The main OECD contributor is the USA, which accounts for 22% of world CO_2 emissions. And despite efforts to curb greenhouse gas emissions, the situation is getting worse.

The OECD countries have a significant share of the world's renewable energy, and are developing their renewable resources rapidly, especially in "new" areas such as wind power and PV. Much still needs to be done, however, if these countries are to achieve sustainability in the energy sector.

[7] The European Trading System for CO2 allowances will be part of the regulatory framework.

6.2 China, India and other rapidly developing countries

Xianli Zhu, Subash Dhar, Kirsten Halsnæs, UNEP Risø Centre, Risø DTU

6.2.1 Economic and social development

Despite fluctuations in global economic growth, some countries' economic growth consistently outperforms that of others. These rapidly growing economies are powerhouses for regional economic growth. Through market reforms, their productivity and competitiveness on the global market are increasing. The dynamics and influence of these countries cannot be neglected in an analysis of global economy, energy, and GHG emissions in the coming decades because of their large economic sizes and big populations.

China, India, Brazil, Mexico, South Africa, and other large and rapidly-emerging economies are important forces, shaping global trends in development, energy, and climate change mitigation. The enormous investments in energy infrastructure in these countries in the years to come will provide a rare window of opportunity for low-carbon development and low-cost reductions in greenhouse gas emissions. At the same time, they face the challenge of supporting economic growth and eliminating poverty for billions of people in a world already facing many constraints on energy and carbon emissions.

Of all the emerging economies, China and India deserve special attention due to their huge populations, large economies, and remarkable economic growth over the last three decades (Table 6). This section will examine the recent trends in the economic, energy, and climate development in China and India and sets the stage for the analysis of the future energy system and climate implication analysis in the next chapter.

6.2.2 Energy consumption and CO_2 emissions in China

A profile of the energy consumption and CO_2 emissions of China and India could be summed up as: large aggregate, low per capita, low efficiency, high coal dependence, and rapid growth. China and India, with their large territory area, population, and economy, are the biggest energy consumers and CO_2 emitters amongst the developing countries. In 2005, 15.2% of the world total primary energy supply was consumed in China, contributing 18.8% of the global CO_2 emissions from fuel combustion. India consumed 4.7% of the world total primary energy consumption and emitted 4.2% of the global CO_2 emissions from fuel combustion [2].

In per capita terms, China and India are characterised by lower-than-world-average energy consumption and GHG emission (Table 7). In India, over 400 million people still have no access to electricity. In both countries, a large share of the population is relying on non-commercial energy for cooking and heating and the ownership of cars and electrical appliances is lower than in OECD countries.

To create the same value of GDP, China and India use more energy. To produce 1 USD of GDP (on exchange rate basis), China and India consume over 4 times of the energy in

Table 6
China and India in the World, 2006 [1]

	China			India		
		World ranking	% of World total		World ranking	% of World total
Population	1,314 m	1	20.1	1,112 m	2	16.8
GDP (PPP) (USD)	8.18 trillion	2	13.7	3.70 trillion	4	6.2
GDP (official exchange rate) (USD)	1.79 trillion	6	4.1	0.72 trillion	12	1.7

Table 7
Per-capita GDP, energy consumption and CO_2 emissions for China and India: a snapshot from 2005 [3]

	China	India	World average	OECD average
Per-capita CO_2 emissions (t)	3.88	1.05	4.22	11.02
Per-capita energy consumption (toe)	1.32	0.49	1.78	4.74
Per-capita GDP (USD 2000 PPP)	6,012	3,071	8,492	25,880
TPES[1] /GDP (exchange rate) (tOe per thousand USD 2000)	0.83	0.83	0.32	0.20
TPES[1] /GDP (PPP) (tOe per thousand USD 2000 PPP)	0.22	0.16	0.18	0.21
CO_2/TEPS (t CO_2 per tOe)	2.94	2.14	2.33	2.37
CO_2/GDP (kg CO_2 per 2000 USD PPP)	0.65	0.34	0.50	0.43

OECD countries. This is due to the lower efficiency in electricity and heat generation, and end use energy consumption. Another reason is that in China, over half of the GDP comes from the industrial sector, which in most cases is more energy intensive than agricultural and service sectors.

On PPP (purchasing power parity), the picture is slightly different. The energy intensity of Chinese economy (TEPS/GDP) is 16% higher than the OECD level [3]. In contrast, the energy intensity of the Indian economy is 11% lower than that OECD average [3]. This is because in India, agriculture and service sectors contribute a much bigger share of the country's GDP. In addition, the households are characterised by low incomes which result in low vehicle and appliance ownership.

In both China and India, a large share of the energy supply is from coal, which emits more CO_2 to generate the same amount of electricity and heat than natural gas and oil. The carbon intensity of energy, i.e., ton of carbon per toe of energy consumed for China is 26% higher than the OECD average whereas for India this is 8% lower than the OECD average. During 2005, in China, 78% of the electricity generation is based on coal, and in India, the share is 69% [2]. The carbon intensity of energy in India is lower because the wide use of biomass and waste is an important source of energy, especially in the household sector. In 2004, 13.6% of China's total primary energy supply was from combustion of renewable and waste, while in India the share was as high as 37.4%, which significantly lowered the CO_2 intensity of India's energy consumption [2].

The fourth and most important feature in the Chinese and Indian energy consumption and associated CO_2 emission is the rapid increase in total amount. As shown in Figure 12, the Chinese economy grew more than 16-fold between 1971 and 2005, while that of India expanded around five-fold. Improvements in energy efficiency and the growth of low-carbon energy sources have been unable to keep pace with this growth, so both energy demand and CO_2 emissions grew. China, however, has to a remarkable extent decoupled economic growth from energy consumption. From 1971 to 2005, China's CO_2 emissions increased by 489%, but over the same period its GDP on a purchasing power parity (PPP) basis went up by 1,038%. In India the effect was less pronounced, but CO_2 emissions growth of 410% was still considerably less than the 454% increase in GDP (PPP basis) over the same period.

China's performance notwithstanding, experiences from a range of countries show strong links between GDP growth and energy consumption. India's economic take-off began around ten years after that of China, but as Figure 12 shows, it seems to be following a similar development curve. The growth trends for per-capita energy consumption and per-capita GDP have been similar for the two countries, though the transformation in China has been much faster than in India. In the case of China, energy consumption rose sharply when per-capita GDP (PPP) reached USD 3,000 in 2002; according to an ADB study, this figure is the tipping point for an increase in vehicle ownership [2]. If this holds true for India, we can in due course expect a sharp upturn in energy demand from the transport sector.

Figure 12
Growth in GDP, total primary energy supply and CO_2 for India & China
(UNEP Database from Sustainable Development, Energy and Climate project)

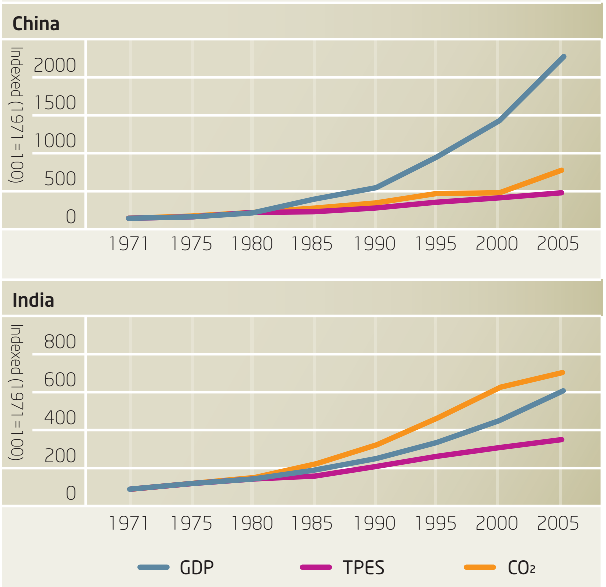
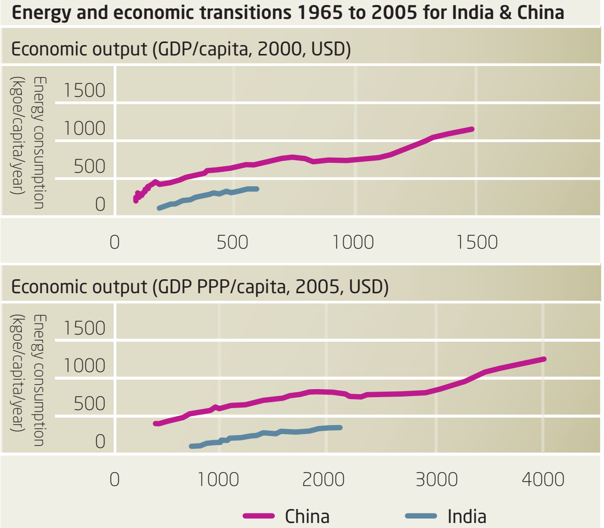
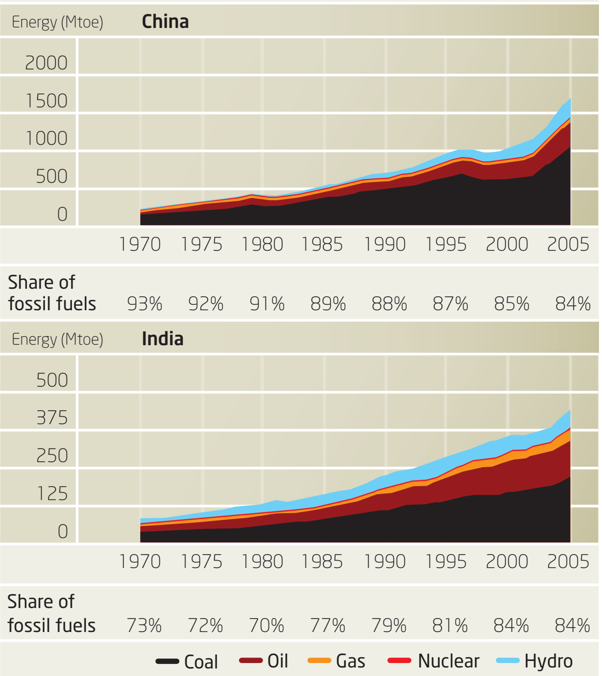


Figure 13
Energy and economic transitions 1965 to 2005 for India & China



Source: GDP [4], Population [5] and Energy [6]

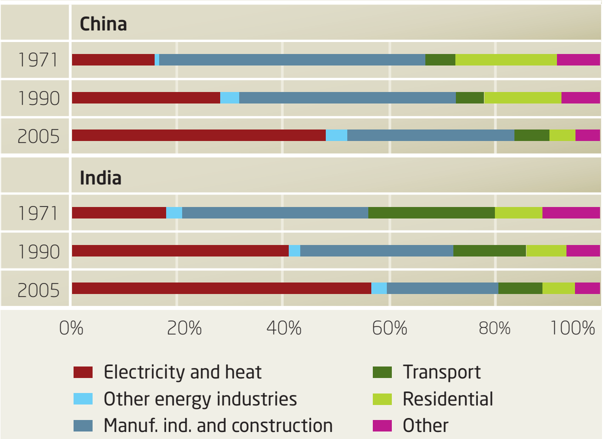
Figure 14
Growth in commercial energy for India & China
Renewables including solar, wind and biomass are not included, since they accounted for less than 1% of commercial energy in 2005 [6]



As Figure 12 shows, CO_2 emissions in both China and India have been growing faster than energy supply. This is because these countries are highly dependent on fossil fuels, especially coal, to meet their energy needs (Figure 14). China and India both have large coal reserves and small reserves of oil and natural gas, so coal, the fossil fuel which emits much more CO_2 for the same energy output, is the main fuel for power generation [2].

Figure 15 shows that in both countries, the share of total CO_2 emissions attributable to electricity and heat production has increased significantly since 1971. The manufacturing sector is another major source of CO_2 emissions. Together, these two industries contribute around 80% of total CO_2 emissions in both China and India.

Figure 15
CO_2 emissions by sector [2]



The significantly larger share of CO_2 emissions from the Chinese industrial sector can be explained by comparing the two countries' economic structures. In China, a much larger share of GDP is generated by industry, reflecting China's role as a world manufacturing centre with a big export market. In India, industry is currently less important to overall economic growth than the service sector, though the share of GDP attributable to industry has been increasing since 1970. In both countries, agriculture has become less important to GDP (Table 8).

Despite the growing prosperity of China and India, per-capita electricity consumption is still much lower than in OECD countries. Per-capita electricity consumption in 2003 was 1,440 kWh for China and 594 kWh for India, compared to the OECD average of 8,777 kWh [5]. China has had a government-led rural electrification programme since the 1980s, and as a result, more than 98% of the country's population has some kind of grid access. Similar policies in India have had limited success, and by 2005 only 74% of Indian villages had been electrified [7].

Table 8
Structure of Chinese and Indian economies [4]

Country	Sector	1970	1990	2005
China	Agriculture	35%	27%	13%
	Industry	40%	42%	48%
	Service	24%	31%	40%
India	Agriculture	42%	29%	18%
	Industry	21%	27%	28%
	Service	37%	44%	54%

Rapid population growth and urbanisation have helped push up energy consumption and greenhouse gas emissions (Table 9). Although population growth in both India and China has slowed, the large population and relatively young age distribution mean that both countries' populations will continue to grow in the next few decades. In China, with its population control policy, average annual population growth has declined from 2.21% during 1970–1975 to 0.67% during 2000–2005 (http://esa.un.org/unup) [8], but the population still grew by 8 million in 2005 [9]. In India, population growth is even faster, and population growth boosts demand for energy.

Both China and India still have large numbers of rural people who rely on firewood and agricultural wastes as their

Table 9
Population growth and urbanisation [8]

		1970	1980	1990	2000	2005
China	Population (m)	831	999	1,149	1,270	1,313
	Urbanisation	17.4%	19.6%	27.4%	35.8%	40.4%
India	Population (m)	549	689	860	1,046	1,134
	Urbanisation	19.8%	23.1%	25.5%	27.7%	28.7%

main source of fuel for cooking and space heating. With ongoing urbanisation, ever more of these people are moving to cities, where they are more likely to use commercial energy for cooking and heating. Urbanisation also drives up the demand for housing, schools, transport and other energy-consuming infrastructure.

6.2.3 Energy and climate change on national development agenda

The existing energy and climate policy initiatives in China and India are designed mainly to improve energy security and reduce local pollution. Even given China's ambitious targets for energy efficiency and renewable energy, these two countries' strong economic growth is very likely to yield continued rapid rises in energy consumption and CO_2 emissions. Aligning GHG mitigation without undermining efforts to climb out of poverty remains an enormous challenge for China, India, other developing countries, and indeed the world as a whole.

China has set two ambitious energy targets to address the problems of resource constraints, local pollution and national energy security:

- ***Energy efficiency***: reduce energy intensity by 20% during 2006–2010, and by 50% during 2003-2020 (China 2020 Energy)
- ***Renewable energy***: enlarge the share of energy from renewable sources in the total commercial energy supply from 7% in 2002 to 10% in 2010, and then to 15% by 2020, and increase the proportion of electricity from renewable sources (China 2020 Renewable Energy Development Programme)

These are extremely ambitious targets. It is estimated, for instance, that the renewable energy target alone will require China to invest around 185,000 million USD (1.5 trillion RMB) in the period 2006-2020.

China has put in place a wide variety of policies and measures to stimulate energy efficiency and renewable energy investment. These include legislation, mandatory energy intensity targets for each province, mandatory elimination of energy-inefficient industrial processes and production capacity, voluntary agreements, subsidies, and preferential tax treatment.

India's five-year plans also include low-carbon development. For example, in the plan for 2002–2007 India set two major targets for renewable energy:

- Commission 14.4 GW of new hydropower and 3 GW of other renewable electricity, out of a total generating capacity increase of 41.1 GW between 2002 and 2007; and
- Electrify 62,000 villages by 2007 through conventional grid expansion, and the remaining 18,000 villages by 2012 using decentralised non-conventional sources such as solar, wind, small hydro and biomass

Table10 lists some of the measures taken by China and India to cut growth in energy consumption and encourage renewables.

6.2.4 Conclusions

China and India are the two largest representatives of a group of countries experiencing rapid economic growth. Although India's economic take-off began around a decade later than that of China, it seems to be following a similar development curve.

The two nations have several features in common that are relevant to energy and climate issues. Their large sizes and populations, for instance, mean that their aggregate energy use and greenhouse gas emissions are already among the largest in the world, and thanks to rapid economic development, both these measures are growing much faster than the world average. At the same time, per-capita energy consumption and greenhouse gas emissions are still low, and both countries still have enormous numbers of people who will be affected adversely by climate change.

The Chinese and Indian governments have already begun to address the economic, social, and environmental problems caused by their countries' rapid energy growth. China, es-

Table 10

Chinese and Indian policies with significant greenhouse gas mitigation effects

Sector	China	India
Power	Higher grid upload tariff for electricity from renewable sources Require grid companies give priority to purchase electricity from renewable sources Gradually tighten energy efficiency standards for electricity generation Plan to to close 50GW of inefficient thermal power plants by 2010 Government investment in nuclear power plants Reduce subsidies to fossil fuel	Tariff-based bidding for large thermal power plants Import of supercritical generating technology will improve efficiencies and lower CO_2 emissions Coal washing plants to improve coal quality, leading to lower SOx emissions and lower CO_2 emissions through improved efficiency Incentives for renewables Proposal to import hydropower from neighboring countries
Industrial	Energy efficiency targets for energy-intensive products and major energy-consuming equipment Energy efficiency labeling Prererence to energy efficient equipment in government purchases Binding energy efficiency targets for 1,000-plus large energy-intensive enterprises	Energy Conservation Act to promote energy efficiency through energy audits, benchmarking and raising the profile of this issue
Transport	Lower purchase tax for energy-efficient cars Build public transport infrastructure in cities Subsidise public transport	Jawaharlal Nehru Urban Renewal Mission (JNNURM) has proposals to improve public transport in major cities
Building	Mandatory energy efficiency standards for new and existing buildings Government-subsidised renovation schemes to increase energy efficiency	Bureau of Energy Efficiency (BEE) has imposed mandatory energy labeling of all electrical equipment, with the aim of raising consumer awareness

pecially, has made very ambitious plans for energy efficiency and renewable energy development. Considering the size of the challenges, however, the existing measures are not enough. Getting these two countries onto the track of low-carbon development will require more effective policies to ensure technology transfer as well as rapid technology development and deployment.

6.3 Africa

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Most of the nations of sub-Saharan Africa (SSA), with the notable exceptions of South Africa and a few others, fall into the category of "least developed countries" (LDCs), typically with per-capita GDP below USD 2,000. Table 11 shows key indicators for some selected LDCs.

LDCs are characterised by industrial sectors that provide only a small proportion of GDP. Although the contribution of agriculture to GDP also appears low, most people in these countries depend largely on agriculture for survival. Poverty levels—the fraction of people with an income below 1 USD per day—are in general above 40%. While provision of basic services like clean water and sanitation is improving in many LDCs, access to modern forms of energy like electricity and gas remains extremely low.

The low level of economic development determines the low level of energy consumption, and also the forms of energy used (Table 12). Sub-Saharan Africa has one of the world's lowest per-capita consumption rates of modern energy, and even this is declining, since the rate of electrification cannot keep pace with population increase. The low level of electrification is due to a number of factors including poverty in general, a highly-dispersed rural population, a low degree of industrialisation, a historically inefficient energy sector, and difficulties in accessing capital to finance the development of modern energy sources [3].

For LDCs throughout this region the major part of energy is used in households as Table 13 shows. By far the largest part of this energy is used for cooking and comes from traditional biomass such as firewood, charcoal and agricultural waste, which supplies as much as 95% of all energy consumed in some countries, and an average of 81% for the whole SSA region.

The major developmental challenges for all the countries in the region may be expressed in terms of the Millennium Development Goals (MDGs). Although there is no specific

Table 11
Key indicators for selected LDCs of sub-Saharan Africa. Gross Domestic Product (GDP) is expressed in Purchasing Power Parity (PPP).
(Africa Economic Outlook, [1] (all except electricity access), World Energy Outlook [2] (electricity access data); assuming a 70/30 rural/urban population split)

Country	Population (m)	GDP per capita (USD, PPP)	Access to electricity (%)	Access to clean water (%)	Access to sanitation (%)	Literacy (%)	GDP contribution from industry (mining and manufacturing) (%)	GDP contribution from agriculture (%)
Burkina Faso	13.6	1,314	7	88.3	9.9	12.8	15.9	17.9
Mozambique	20.2	1,957	6.3	40	34		13.7	21.4
Zambia	11.9	1,167	19	62	27		14.2	9.6
Tanzania	39.0	594	11	59.8		69.4	9.6	17.9

Table 12
Primary energy consumption of selected LDCs in SSA in 2005
(International Energy Agency [4]; data from Burkina Faso is from 2004 [5]; generating capacity is from SADC [6] and MMCE [7])

Country	Total primary energy consumption (ktoe)	Biomass (%)	Coal (%)	Oil and gas (%)	Other (renewable) (%)	Electricity imports as a fraction of total primary energy (%)	Electricity generating capacity (2002) (MW)	Electricity consumption (GWh/y)
Burkina Faso	3,054	85.4		14.0	0.3	0.3	136	546
Mozambique	10,207	85.4		5.4	11.2	-2.0	2,388	9,143
Zambia	7,124	78.7	1.3	9.5	10.7	-0.2	1,778	
Tanzania	20,404	92.1	0.2	6.9	0.7	0.1	881	2,256

Table 13
Sectoral energy split in selected LDCs in SSA in 2005
(percentage of total final energy consumption) (International Energy Agency [4]; data from Burkina Faso is from 2004 [5])

Country	Households	Industry	Agriculture	Commerce, service sector	Transport	Other
Burkina Faso	81.8	10.1		0.7	6.8	0.5
Mozambique	78.0	17.1		0.4	4.4	0.1
Zambia	66.7	24.1	0.3	1.7	6.3	0.8
Tanzania	79.5	10.3	4.4		2.5	3.3

MDG for energy, it is now widely accepted that access to energy contributes, and is indeed essential to the achievement of all the MDGs. Thus, access to clean, affordable and reliable energy is a prerequisite for the countries of SSA, not only for household uses like cooking, heating and lighting, but also for industry and agriculture, social services and transport. It is through the productive use of energy, in the broadest sense including energy for education, health and other social services, as well as for income-generating activities, that these populations can be helped out of poverty to lead rich and fulfilling lives.

With regard to the climate change problem, the LDCs of SSA contribute very little to global greenhouse gas emissions, and this is likely to remain the case into the foreseeable future. The overriding issue is how to provide increased energy for development. While the emission of greenhouse gases like CO_2 is not the main driver for energy policy in SSA, it would be wise even at this stage to replace high-carbon fuels with low-carbon alternatives such as natural gas, and to include CO_2-free renewable energy, as long as these solutions are close to being economically competitive. In such cases, carbon financing schemes such as the Clean Development Mechanism (CDM) might provide supplementary funding for new energy developments.

Two main challenges are apparent in the energy sector:

- How to provide access to clean, modern energy to growing populations, often in dispersed rural settlements, as well as social services and growing industries
- How to ensure a reliable and stable energy supply, in the wake of recent energy shortages. These have been caused by, for example, water shortages in hydropower-dependent countries such as Ghana and Tanzania, rising oil prices, and the recent power shortfall in South Africa, which has seriously affected neighbouring countries to the north

6.3.1 Energy on the development agenda

Each LDC in SSA has different priorities and different resources, and each will need different approaches to meet the two challenges referred to above. In general, however, the key is to mobilise financial resources, both internal and external, to allow investment in energy infrastructure.

Tied to this is the need to place energy firmly on the development agenda alongside other necessities like health, education, roads and water supply. This will encourage both internal investment stakeholders (such as banks and private-sector companies) and international development agencies to treat energy as a priority and to channel the required funding towards energy development. Wherever possible it is certainly advantageous to tie energy investment to other sectors like education, health and industry; multi-sectoral involvement helps scarce resources to be used in the best way possible.

There are indications that energy is indeed moving up the development agenda and being reflected in donor priorities. The latest Poverty Reduction Strategy Papers (PRSPs), for instance, recognise the importance of energy. An encouraging development in recent years has been a growing attention to energy in EU-based assistance. The EU Energy Initiative has since 2005 channelled about €200 million to energy projects in SSA, and we can hope that the recently-agreed Africa-EU Energy Partnership will increase dialogue, cooperation and resources for African energy development. Likewise, initiatives in the World Bank, UN organisations like UNDP and UNIDO, and a few bilateral donors such as the German BMZ/GTZ are giving renewed priority to energy development.

6.3.2 Energy resources and supply

Africa as a whole is endowed with vast fossil energy resources, especially coal and natural gas. The ratio of resources to production is over 194 for coal, over 78 for natural gas and 32 for oil, compared to global figures of 147 for coal, 63 for gas and 41 for oil [8]. New discoveries of oil and gas have grown by 46% and 34% respectively in the past 20 years [8], and this trend continues, most recently in Ghana where significant offshore oil resources have been identified [9].

In addition to its fossil-fuel reserves, Africa has 20% of the world's known resources of low-cost uranium, mostly in Namibia (27% of the African total) and South Africa (38%). Nuclear power, however, is likely to be confined to South Africa. Africa also has 11% of the world's technically-exploitable hydropower resources, concentrated in the Great Lakes region and in countries along the Atlantic coast from Guinea to Angola. The Democratic Republic of Congo alone has 42% of Africa's technically-exploitable hydro resources [10].

Wood fuel is extensively used in Africa, especially in SSA where it provides 70-90% of final energy consumption. The current consumption of wood fuel in Africa is estimated at 5,600 PJ, or 31% of the global total [10]. Most SSA countries have had programmes for reforestation and dissemination of energy-efficient wood stoves since the droughts of the 1970s and 1980s [11].

There is a growing consensus that the so-called fuel-wood crisis has been exaggerated, and that observed depletion of forests is often caused by broader changes in land use [see e.g. 11, 12, 13, 14]. Depletion of forest resources, however, is still a major concern around cities and large towns, and in areas where charcoal is made [11]. We need better data on the loss or gain of African forests, but wood fuel and agricultural wastes are increasingly considered to be sustainable energy resources that help to alleviate poverty rather than cause it [11].

Modern biomass comprises bioethanol, biodiesel, biogas and agricultural wastes, all of which Africa is well placed to produce. Widespread use of modern biomass has so far been hindered by high capital costs, lack of institutional and policy support, and inadequate research [15]. While reasonably successful in other developing countries, biogas for household applications has not so far played an important role in Africa. A major challenge for biofuel production in developing countries remains the possibility of competition for land between the biomass and food crops. There are, however, promising ways to maintain food production while increasing the production of biofuels, e.g. by using marginal lands for biofuels and improving crop yields by intensifying farming systems in SSA [16].

Electricity production in Africa is 3% of the global total. In Africa as a whole, thermal generation dominates and is foreseen to do so until 2030. Coal-fired power plants, for instance, accounted for 45% of generating capacity in 2004 and are projected to settle at 46% in 2030. Generation from natural gas is expected to increase from its current figure of 25% to 38% by 2030 [16]. However, most of this coal and natural gas generation is, and will continue to be, in South Africa, the other coal-producing countries of Southern Africa such as Botswana and Zimbabwe, and the oil-producing countries of Nigeria and North Africa.

Considerable natural gas resources are now being discovered in the Southern African countries of Namibia, Mozambique and Tanzania. For the foreseeable future these resources will be able to cater for the high demand of South Africa and the neighbouring countries of the Southern African Development Community (SADC). Nevertheless, for the majority of LDCs in Africa, coal and other fossil fuels have to be imported. With rising oil prices, these countries are increasingly looking to renewables as the cheapest option.

Next after coal and natural gas as sources of electricity comes hydropower. Most LDCs rely on hydro, but at a capacity that is limited by lack of funding or international support for large commercial projects. This is in spite of the high priority hydropower is given by major regional players including the African Union and the Regional Economic Communities [17]. Countries that are largely dependent on hydropower, such as Tanzania and Ghana, have also experienced interruption in supplies from frequent years of drought. The trend then has been to resort to diesel generation in the short term and to build thermal power stations in the longer term.

6.3.3 Other renewable energy sources

There are promising solar, wind and geothermal resources in many parts of Africa, but in the SSA region these alternatives are being accepted and taken up very slowly, mainly due to the high investment cost. Current figures show about 500,000 solar home systems (SHSs) in Africa, concentrated in a few countries with specific SHS programmes. Kenya has about 200,000 units, South Africa about 150,000, Zimbabwe 85,000, Morocco 37,000 and Uganda about 20,000 [18, 19]. Wind resources are generally located in coastal regions, but so far wind has only been exploited on a large scale in Egypt (230 MW) and Morocco (124 MW) [20]. Geothermal energy could also make a considerable contribution, with an estimated potential of 2.5–6.5 GW, although so far only 129 MW in Kenya has been tapped [21].

The recent rise in oil prices, from 20–30 USD per barrel from 1985–2003 to the current high level, may dramatically change this situation. Besides an increased focus on SHSs, wind parks and geothermal energy, hybrid systems consisting of small-scale hydro, wind or solar PV in combination with diesel may be a least-cost option for mini-grid systems in the future [22].

6.3.4 Conclusions

The key drivers shaping energy development in the LDCs of Africa are:

Energy access (for poverty alleviation, income generation, industrial development and social services) is increasingly recognised as essential to achieving the MDGs, even though this is unlikely to happen fully in the SSA countries within the 2015 timeframe. Inclusion of energy access in poverty reduction plans is becoming widespread, though so far only a minority of countries regard energy as a high priority. There is little doubt that the way forward lies in electricity access for the majority, whether from central grids or decentralised, often with clean fuels like LPG as a supplement for heating and cooking.

Energy security has become a crucial issue, particularly following the Southern Africa power crisis, but also in West and East Africa due to water shortages limiting the energy available from hydropower. Significant coal-fired capacity (over 15 GW) is planned for immediate development within the Southern African region to bridge the capacity gap.

Continuing coal use: According to Shell Energy Scenarios to 2050, oil and gas are to peak at global level in 2015–2020, but the demand for coal continues regardless of the quest to curb carbon emissions [23]. In the case of Africa both resource uncertainty and the prospect of increasing oil prices favour continuing coal use particularly for electricity generation. In this context, cooperation in the form of regional power pools is important; this has already become evident in subregions of SSA such as the Southern African Power Pool and the West African Power Pool [24].

Climate change, while important as far as impacts and adaptation are concerned, does not in itself appear as a priority driver in SSA energy policy, since per-capita energy consumption and CO_2 emissions are low. Moreover, since it is developmentally essential to increase energy consumption, there is little political incentive to reduce emissions. Neither is there any obligation within the Climate Convention. Nevertheless, climate change is relevant in view of the likely baseline scenario which, as argued above, is likely to involve significant coal and oil use. There will thus be increasing opportunities for cooperation with industrialised countries, through carbon financing, to invest in cleaner low-emission energy technologies, including clean coal, gas, biomass and other renewables, where appropriate.

Economic development of African LDCs will inevitably occur at different paces, depending on factors including resource availability, internal political priorities, connection to regional "locomotives" like South Africa, and geopolitical factors. Accompanying such development, as well as driving it, will be an increased demand for energy. The most obvious energy resources to meet immediate needs are fossil fuels: coal, oil and natural gas. However, Africa has vast resources of biomass and hydropower, and, given the necessary investment and technological development, these resources could be exploited both for domestic use and as major earners of export revenue.

Future energy systems to cope with climate and energy challenges

7

7.1 OECD countries

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We are facing serious challenges in the energy sector. The global economy is set to grow fourfold between now and 2050, and growth could approach ten-fold in developing countries like China and India. This promises economic benefits and huge improvements in people's standards of living, but also involves much more use of energy. Unsustainable pressures on natural resources and on the environment are inevitable if energy demand is not de-coupled from economic growth and fossil fuel demand reduced.

A global revolution is needed in the ways that energy is supplied and used. Far greater energy efficiency is a core requirement. New renewable energy sources and carbon-free technologies have to be developed. A dramatic shift is needed in government policies, notably creating a higher level of long-term policy certainty over future demand for low-carbon technologies, upon which industry's decision-makers can rely. Unprecedented levels of cooperation among the world's major economies will also be crucial, bearing in mind that under the "business-as-usual" scenario for 2050, less than one-third of global emissions are expected to stem from OECD countries.

Increasing concerns over climate change and security of supply imply that our energy systems will have to change drastically in the future. Renewable energy sources including wind power, photovoltaics (PV) and biofuels will need to make significant contributions to our energy systems, alongside traditional sources such as coal, oil and natural gas.

Renewable energy technologies such as wind power and PV are characterised by inherent variability of production. This will increase the complexity of future energy systems, and introduce the need for advanced features including demand response, regulation and storage. This in turn calls for advanced modelling techniques to support decisions on how to develop future energy systems. Most of these decisions will have consequences lasting for 30–40 years or even longer, so it is of the utmost importance that they are based on sound reasoning and accurate calculations.

Modelling energy systems over large regions of the world is a complicated matter, so only a limited number of energy studies and models exist. Some of the more important ones are the World Energy Outlook and the Energy Technology Perspectives undertaken by the IEA; the long-term scenarios reported by the Intergovernmental Panel on Climate Change (IPCC); the studies prepared by the World Energy Council (WEC); and work carried out in relation to European Union policy. For this Energy Report we have chosen to focus on the IEA Energy Technology Perspectives because of its timeliness and long-term view.

7.1.1 Energy Technology Perspectives

Energy Technology Perspectives (ETP 2008) [1] is an in-depth review of the status of, and outlook for, existing and advanced clean energy technologies. It draws on modelling work within the IEA Secretariat and expertise from the IEA's international energy technology collaboration network. ETP 2008 is a companion to the IEA's World Energy Outlook 2007 [2], taking that publication's reference ("baseline") scenario and extending it from 2030 to 2050.

ETP 2008 presents several different sets of scenarios. The "ACT" scenario shows how global CO_2 emissions could be brought back to current levels by 2050, while the "BLUE" scenario targets a 50% reduction in CO_2 emissions by 2050. Only the BLUE scenario will be described here.

The main assumptions of the BLUE scenario are:

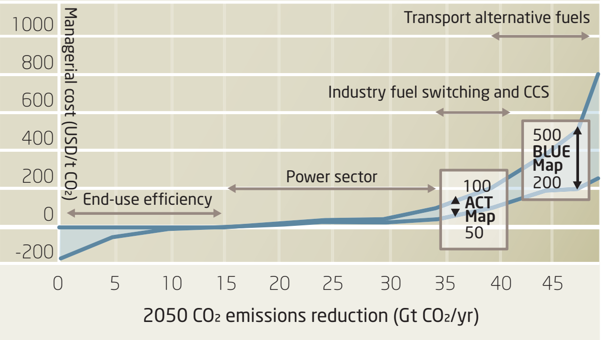
- Global population is assumed to grow at 0.8% /y from 2005 to 2050. OECD population is assumed to grow by 0.2% /y in the same period, reflecting continued growth in North America, slow growth in the EU and a decline in the OECD Pacific region
- GDP is worldwide assumed to grow by 3.3% /y from 2005 to 2050. The main growth will be in develop ing Asia, with approximately 5.2% /y in China and India. Growth in the OECD is assumed to average 1.9% /y, with the highest growth in North America and lowest in Japan

Oil import prices in the baseline scenario are consistent with the World Energy Outlook Reference Scenario: a crude oil price of USD 62–65 bbl and a natural gas price of approximately USD 8/MBtu in 2030–2050 (constant-2006 prices). BLUE assumes lower oil prices, but this is more than compensated for by a CO_2 incentive of USD 200/t CO_2, giving an effective oil price of USD 80/bbl.

Reducing CO_2 emissions by 50% by 2050 is a tough challenge that implies a very rapid change of direction. Costs are not only substantially higher, but also much more uncertain, because BLUE demands the deployment of technologies that are still under development, and whose progress and ultimate success are therefore hard to predict. BLUE requires urgent implementation of unprecedented and far-reaching new policies in the energy sector.

Figure 16 shows how the marginal costs of CO_2 abatement increase as the targeted CO_2 savings increase. For BLUE, the figure is at least USD 200 per tonne of CO_2 saved, and it could be as high as USD 500 if the progress of key technologies is disappointing. The blue area indicates the cost range, bounded by optimistic and pessimistic technology assumptions.

Figure 16
Marginal CO_2 abatement cost curve, 2050 [1]



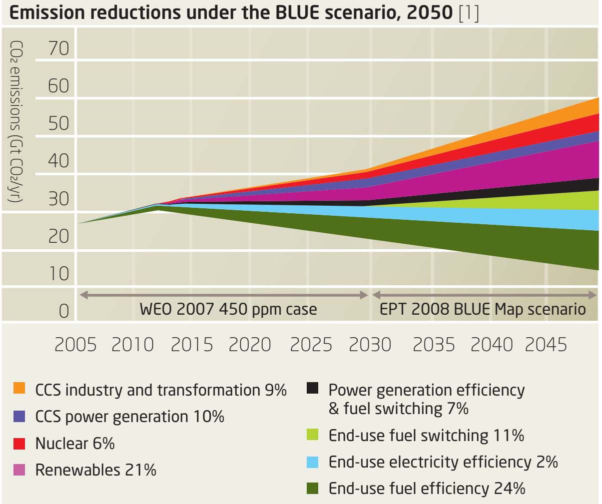
As well as their environmental benefits, the ACT and BLUE scenarios also show a more balanced outlook for oil markets. Under ACT, demand for oil continues to grow, but the forecast increase of 12% between now and 2050 is much less than in the business-as-usual scenario. BLUE shows a much more marked difference, with oil demand 27% less in 2050 than it is today. However, this does not greatly reduce short- and medium-term investment needs in fossil-fuel supply. All the scenarios predict that massive investments in fossil-fuel supply will be needed in the coming decades.

Energy efficiency improvements in buildings, appliances, transport, industry and power generation represent the largest and least costly savings. Next in the hierarchy of importance come measures to substantially decarbonise power generation. This can be achieved through a combination of renewables, nuclear power, and the use of carbon capture and storage (CCS) at fossil-fuel plants. Whichever the final target, action in all these areas is urgent and necessary.

It is particularly important to avoid becoming locked into inefficient technologies for decades to come. The BLUE scenario requires higher-cost options including the industry-sector application of CCS, and alternative transport fuels. Figure 17 shows the sources of CO_2 savings in BLUE compared to the baseline scenario. Policymakers should remember that long lead times are frequently required to implement changes and that priorities in each country will vary according to national circumstances. Moreover, reducing methane emissions in the energy sector is also an important part of an overall climate change strategy, as these emissions offer important opportunities for near-term and cost-effective greenhouse gas reduction.

CCS for power generation and industry is the most important single new technology for CO_2 savings in both ACT and BLUE, in which it accounts for 14% and 19% of total CO_2 savings, respectively. BLUE includes higher-cost applications of CCS for industry and gas-fired power stations. There is a massive switch to renewables for power generation, especially to wind, PV, concentrating solar and biomass, so that by 2050, 46% of global power in the BLUE scenario comes from renewables. Renewable technologies across all sectors account for 21% of the CO_2 savings in the BLUE scenario against the baseline scenario. A substantial switch to nuclear contributes 6% of CO_2 savings, based on the construction of 32 GW of capacity each year between now and 2050. Nuclear accounts for nearly one-quarter of power generation in BLUE, and hydro for half as much, building on the important role both technologies already play in the baseline scenario.

Figure 17
Emission reductions under the BLUE scenario, 2050 [1]



The report's broad range of options for power generation shows that there is considerable flexibility for individual countries to choose which precise mix of CCS, renewables and nuclear technology they will use to decarbonise their power sectors.

The BLUE scenario is very challenging for the transport sector: significant decarbonisation of transport, which has hitherto been dominated by the internal combustion engine, is likely to be much more costly than in sectors such as power generation. BLUE assumes that advanced biofuels will play a significant role, within the limits of sustainable production and cropping. Trucks, shipping, and air transport will be the chief consumers of biofuels, since other non-hydrocarbon options are likely to be very expensive to apply to these transport modes.

Table 14 shows the energy supply and demand consequences of the BLUE scenario for the OECD countries and the world as a whole.

In the BLUE scenario, total primary energy demand in the OECD countries is expected to decline by 0.1% /y from 2005 to 2050, which is significantly lower than the average 1.4% /y growth of the last 15 years. Growth in energy demand from the rest of the world is expected to be much higher, so that the OECD's share of world primary energy demand will decline from almost 49% in 2005 to 34% by 2050.

Demand for oil is forecast to decline by 0.8% /y globally, and at twice that rate (1.7% /y) in the OECD countries. Note, however, that this is an average that encompasses global growth in the next two decades, followed by rapid decline. Owing to new policy initiatives to reduce CO_2 emissions, the demand for coal in the OECD region will decrease at 1.9% /y; world coal use will decline at 0.6% per year.

CO_2-neutral fuels will develop rapidly in the OECD between 2005 and 2050. This applies to biomass and waste, which will grow at 3.7% /y, but especially to other renewables (including wind power and solar), which are forecast to grow strongly at an average 5.7% /y over this time period. Even in this extreme scenario, the OECD countries will still rely heavily on fossil fuels, which will provide 44% of their total primary energy in 2050. The global share of fossil fuels will be 52% in 2050 according to the BLUE scenario.

Accounting in terms of primary energy equivalents has its limitations, as it is heavily influenced by the conventions for conversion efficiency, notably for nuclear and renewable power. An analysis of final energy demand provides more insight into the role of renewables. In Table 15, power generation from renewable sources has been translated into primary energy equivalents using an efficiency of 40%, a reference value for power generation from fossil fuels.

In BLUE renewables in power generation account for 67% of total renewables use in the OECD countries, but only 57% of renewables worldwide.

In the power industry the role of renewable energy sources is forecast to increase significantly, making renewables the largest source of power in this scenario. Globally, renewable energy including hydro will account for 46% of total power generation in 2050, compared to 18% today. For the OECD countries the figures are 50% in 2050 compared to 18% today.

BLUE assumes that biomass will be a key part of the renewable energy supply, and that primary bioenergy use would grow by nearly 200%. The type of biomass would be radically different from today: while the use of traditional biomass will decline, biofuels and bio-feedstocks will grow significantly. In the transport sector, second-generation biodiesel and jet fuel from biomass would become important, since very few sustainable energy alternatives exist for trucks, shipping and aviation.

Emissions of CO_2 are influenced by developments in energy systems in two ways. On one hand, the general increase in energy consumption implies higher CO_2 emissions, while on the other, shifts in the energy mix away from fossil fuels tend to reduce emissions. In the BLUE scenario, CO_2 emissions from OECD countries will total 3.8 Gt in 2050, representing a decline of 71% compared to the present value, or an average decline of 2.7% /y. The global figures are more modest, with an average decline of 1.5% /y until 2050. By 2050 the non-OECD countries would account for 72% of total global CO_2 emissions, and would have reduced their emissions by 27% compared to the 2005 level.

This analysis assumes least-cost decision-making as a basis for the regional distribution of emissions reductions. Other criteria would result in different distributions. Also, the re-

Table 14
World and OECD energy requirements under the BLUE scenario [1]

	OECD (Mtoe)			World (Mtoe)		
	2005	2050	2005-2050	2005	2050	2005-2050
Coal	1,130	476	–1.9%	2,892	2,251	–0.6%
Oil	2,247	1,043	–1.7%	4,000	2,840	–0.8%
Gas	1,211	820	–0.9%	2,354	2,951	0.5%
Nuclear	611	1,259	1.6%	721	2,184	2.5%
Hydro	109	186	1.2%	251	542	1.7%
Biomass and waste	194	1,009	3.7%	1,149	3,604	2.6%
Other renewables	39	470	5.7%	61	1,013	6.4%
Total	5,542	5,263	-0.1%	11,429	15,386	0.7%

Table 15
Development of renewable energy according to the BLUE scenario [1]

	OECD (Mtoe)				World (Mtoe)			
	Final	Final	Primary (equivalents)	Annual growth	Final	Final	Primary (equivalents)	Annual growth
	2005	2050	2050	2005-2050	2005	2050	2050	2005-2050
Hydro	117	186	465	1.0%	256	542	1,355	1.7%
Biomass and waste power	18	81	203	3.4%	27	210	525	4.7%
Geothermal power	7	50	124	4.5%	9	91	228	5.2%
Wind power	20	197	493	5.2%	24	445	1,112	6.7%
Solar power	1	153	383	11.9%	1	409	1,022	14.3%
Other renewables power	0	9	24	10.6%	0	35	89	12.2%
Geothermal heat	4	49	49	5.7%	4	165	165	8.6%
Solar heat	2	49	49	7.4%	3	165	165	9.3%
Biofuels and feedstocks	76	492	652	4.2%	94	1,461	2,301	6.3%
Traditional solid biomass	57	94	94	1.1%	923	588	588	-1.0%
Total renewables		2,535					7,549	

gional distribution of emission reductions is not the same as the distribution of the cost burden. These distribution issues are probably one of the key hurdles to clear in achieving deep emissions cuts. OECD analysis suggests that the cost of implementing the emissions reductions required for the BLUE scenario would result in modest GDP reductions in the OECD countries (-1% in 2050), but much more significant impacts in certain non-OECD countries [3].

7.1.2 Summary

The IEA's Energy Technology Perspectives presents an in-depth review of the status and outlook for existing and advanced clean energy technologies, offering scenario analysis of how a mix of these technologies can make a difference.

The BLUE scenario in ETP 2008 targets a 50% reduction in CO_2 emissions by 2050. Its main points are:

- Reducing CO_2 emissions by 50% by 2050 is a tough target. Achieving it will require the use of a large number of new and existing energy technologies, including renewables, low-carbon technologies and CO_2 storage
- Total primary energy demand in the OECD countries is expected to decline by 0.1% /y from 2005 to 2050, compared to average growth of 1.4% /y over the last 15 years. Future growth in OECD energy demand is also forecast to be much lower than in the rest of the world, so that the OECD share of world primary energy demand will decline from almost 49% in 2005 to 34% in 2050
- OECD demand for oil will decline on average at 1.7% /y, though it should be kept in mind that this is an average that combines demand growth in the next two decades with rapid decline thereafter. By 2050 oil will meet 20% of OECD energy demand, compared to 40% today
- Fossil fuels will continue to be a very important energy source in the OECD countries, providing 44% of total primary energy in 2050. Worldwide, the share of fossil fuels is 52% in 2050
- In terms of their primary energy equivalents, renewable energy sources will account for 50% of total energy supply in the OECD by 2050, compared to 18% today. The main contributors will be wind power, hydro and solar. Renewables will become the largest source of power generation.

7.2 China, India and other rapidly developing countries

Xianli Zhu, Kirsten Halsnæs, Subash Dhar
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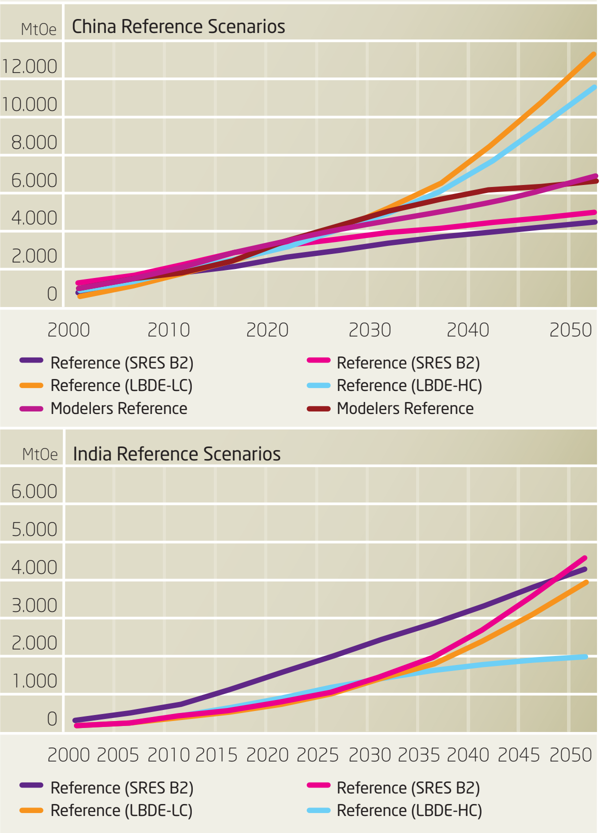
The energy demand growth in rapidly developing countries will be a major driving force for the global energy demand increase. Without significant technology changes in the existing energy systems, satisfying the energy demand in these countries will lead to significant increase in global GHG emissions, however deep the emission reduction could be achieved in OECD countries [1]. This section takes China and India as examples to understand the energy and climate challenges facing rapidly developing countries and identify the key technologies that could help address these challenges. Finally, it examines the importance of international cooperation and carbon finance in speeding up the transfer and deployment of clean energy technologies in rapidly developing countries.

Figure 18
AR4 China and India 2050 primary energy consumption scenarios; prepared by the authors based on data from the Emission Scenarios Database [2]



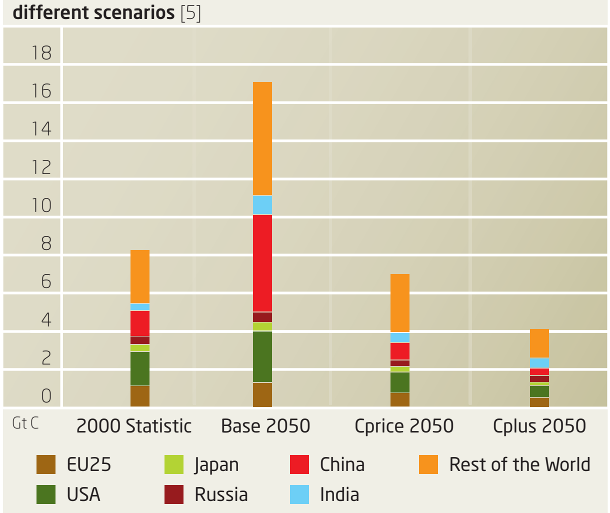
7.2.1 Future energy demand and GHG emissions

To assess the energy and climate challenges facing China and India, the first step is to understand these countries' future energy demand. To date, a wide variety of studies have been carried out to model future energy demand and related greenhouse gas (GHG) emissions for the whole world, as well as its various regions and countries. All these models depend on a few key assumptions: economic growth, economic structure, population growth, energy technology progress, and political intervention.

The SRES Emission Scenario Database (ESD) [2], hosted by the Japan National Institute of Environmental Studies (NIES), compares various GHG emissions models taken from the existing literature [3]. The ESD contains dozens of studies on the future energy demands of China and India, though many studies focus on country groups, sub-continents or continents. Figure 17 shows the scenarios in the ESD that deal with primary energy demand in China up to 2050, as well as the corresponding data for India.

Due to the fact that in India and China, a large share of the energy comes from coal, which is more CO_2 intensive compared with other fuels to provide the same amount of energy, rapid energy consumption growth means significant increases in the GHG emissions from these countries [1, 4]. A recent research project jointly carried out by the UK and Japan examined the GHG mitigation potential among different regions to find out how to accelerate technological change to achieve the G8 targets of 50% reduction in world annual GHG emissions in 2050 from the emission level in 2000. Research results are published in a supplement issue of the journal 'Climate Policy' in 2008. Under that project,

Figure 19
Change in CO_2 emissions in 2050 in different regions among different scenarios [5]



Barker, Scrieciu, and Foxon [5] used the E3MG macro-econometric model and got results in terms of GHG emissions by 2050 (Figure 19).

Under the baseline scenario (Base 2050), the GHG emissions of US, China, India, and other development will see major increase on the 2000 basis, as a result it is projected that the global GHG emissions will double by 2050. In the Cprice scenario, worldwide policy intervention will be introduced, so as to create a global real (year 2000) carbon price of $2.5/ tCO_2 in 2011, rising by $2.5 per year to $100/ tCO_2 in 2050. Consequently, the global GHG emissions will be reduced to less than the 2000 level in 2050. In this scenario, China needs to reduce its GHG baseline 2050 emissions by over 80%, and India by around 50%. Put together these two countries will contribute to almost half of the global emission reduction in annual GHG emissions. However, to realise the G8 target lowering global GHG emissions by 50% on the 2000 basis in 2050, China needs to realize much deeper cuts even on the 2000 level, while India could increase its emissions by almost 60% on its 2000 level.

7.2.2 Key technologies

One key energy challenge facing China and India is how to satisfy robust increases in energy demand over the next few decades, especially for power generation. As Table 16 shows, China and India's share of world fossil fuel reserves are much lower than their share of world population. Large future increases in oil demand, which will occur as a growing part of the population becomes able to afford private cars, will be met mainly by imports from the world market.

Shortage of domestic natural gas reserves is as severe as the shortage of oil reserves in both China and India. The difference with gas is that given these countries' present low consumption, increases in the near future could be satisfied mainly by boosting domestic production. Insufficient domestic supplies of both natural gas and oil mean that applications for these fuels in developed countries, like electricity production, space heating, and cooking, in China and India will have to rely on other sources of primary energy or imports.

Coal is the only fossil fuel for which China and India do not face significant import dependence in the decades to come. Most studies, in fact, indicate that coal will be the most important source of energy in China and India until 2050. The First China National Climate Change Assessment, prepared by over 200 Chinese experts and published by six Chinese government ministries, projects that by 2050, nuclear and renewables could together provide over 30% of the country's primary consumption. With the addition of oil and natural gas, this would mean that the country's dependence on coal for energy could finally be reduced to below 50% [7].

Unless major technology breakthroughs are made, renewable energy will increase only slowly as a fraction of total energy supply. This is due to the fact that traditional biomass is still the main source of fuel for cooking and heating among a large share of the rural population in both China and India.

Converting households to fossil-fuel-dominated commercial energy supply, during the ongoing process of massive urbanisation, will partially offset any increases in modern biomass and other renewable energy sources.

Clean coal technology will be a top priority for the power sectors in both countries. Given their balance of fossil fuel reserves and the current tight market for oil and gas, coal will continue to be the most important energy resource in both China and India, so the clean use of coal will be necessary.

Clean coal technologies include super-efficient coal-fired power plants, coal gasification, and carbon capture and storage (CCS). Such technologies could reduce local air pollution as well as GHG emissions from the use of coal, and are a high priority in the national energy strategies of both countries. Indian coal generally has a high ash content, which significantly reduces the efficiency of power generation in standard boilers. Coal beneficiation (cleaning) technologies are therefore also important for India.

Nuclear currently only plays a marginal role in the electricity supply of China and India. China has 8.6GWe (net) of nuclear power units in operation, providing 62.86 billion kWh - 2.3% of its total electricity generation in 2007. In India, 2.5% of the electricity was generated from nuclear in 2005 [1], the

Table 16
Fossil fuel reserves, production and consumption for China and India, 2006 [6]

Fuel	China				India			
	Proven reserve	% of World total	Reserve / production	Production / consumption	Proven reserve	% of World total	Reserve / production	Production / consumption
Oil	16.300 bn barrels	1.3%	12.1	53%	5.7 bn barrels	0.5%	19.3	31%
Gas	2.45 trillion m^3	1.3%	41.8	105%	1.08 trillion m^3	0.6%	33.9	80%
Coal	114.5 bn tons	12.6%	48	102%	92.4 bn ton	10.2%	207	88%

Table 17
Biomass and waste combustion for energy supply in China and India, 2004 [8]

	Total (Mtoe)	Share of residential energy consumption	Share of total primary energy consumption
China	219.1	68%	14%
India	189.9	83%	33%

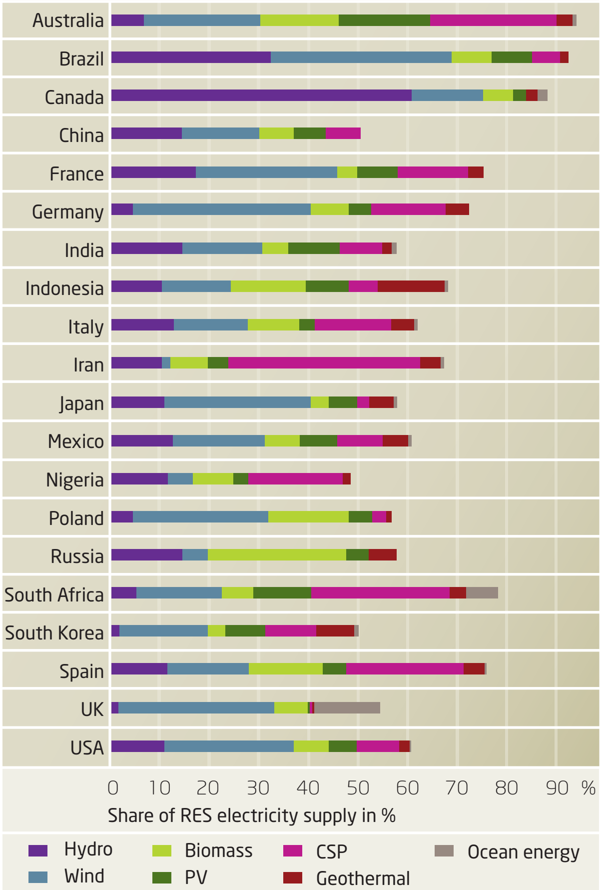
country's installed capacity of nuclear power generating units had increased, to 3.6 GWe in 2006. Uranium is more widely distributed around the world than are oil and gas, and high import dependence does not lead to the same level of concern over supply security. In both China and India, nuclear is taken as an important means for improving long-term energy security and reducing dependence on international oil and natural gas import. Both countries have made ambitious plans for nuclear power development. China's latest target is increasing its nuclear capacity to 60GWe, or 6% of the country's total installed generating capacity in 2020, then further to 160GWe in 2030. The Indian government's nuclear power generation programme sets the ambitious target to raise nuclear power generation capacity to 20 GW by 2020 and to 40 GW by 2030. The 'Integrated Energy Policy' report [9] prepared by the Expert Committee of the Indian Planning Commission recommends that if the nuclear cooperation agreement between India and the US could eliminate sanctions from nuclear suppliers against India, the Indian government should actively import nuclear power plants and fuel, and make nuclear power the most potent means of improving long-term energy security and achieve energy independence by utilizing its vast thorium resources.

The development of renewable energy depends very much on the availability of suitable resources. For China the key technologies for renewable electricity will be hydro and wind. In India, it will be hydro, wind, solar PV, and concentrating solar power (CSP), thanks to the country's abundant sunshine (Figure 20).

With their large territories and population bases, rapid economic growth and rising living standards, China and India are seeing rapid growth in freight and passenger transport. They are already home to several of the world's "super-cities" and massive urbanisation ensures that many other cities continue to expand and new ones spring up. In view of these nations' shortage of oil reserves, clean vehicles and public transport will be the key technologies in tackling the fourfold challenge of oil supply, local air pollution, traffic congestion and GHG emissions.

On the energy demand side, various energy efficiency technologies will play a major role in slowing the increase in energy demand and GHG emissions. China and India, like other developing countries, generally use energy relatively inefficiently. China's average energy conversion and utilisation efficiency is around 25% lower than that of developed countries, and in 2000, the energy consumed per unit of production in the Chinese electricity, steel, non-ferrous metal, petrochemical, building material, chemical, and textile industries was around 40% higher than the international benchmark [7]. There is huge potential for improving energy efficiency in the industrial, residential and commercial sectors.

Figure 20
Potential of renewable energy for electricity supply in large economies by 2050 [10]



7.2.3 International technology transfer and carbon finance

In both countries, lots of new investments are being made and will be made on electricity generation, infrastructure facilities and building construction, large increases in private cars, and electrical appliances. These new investments offer more cost-effective opportunities for emission reduction than the early retirement of low-efficiency products. Due to these factors, as shown in Figure 21, the GHG emissions of China and India as well as other developing countries could be significantly reduced in relation to their baseline scenario at a carbon cost of 50 US$/t$CO_2$.

In China, India, and other rapidly developing countries, a common reality is that they still have a large poor population. Economic development, poverty alleviation, reliable and affordable energy supply to their citizens, and local air pollution control are often of high political priority to the national governments. A lot of measures could contribute to climate change, e.g. early retirement of low efficiency energy production or consumption equipment and replacing them with new ones, or a switch to cleaner energy, or choosing advanced technology and equipment.

Moreover, the majority of the existing GHGs in the atmosphere were emitted by developed countries in the course of their industrialisation and development since the 1750s. Meanwhile, developing countries, which are less responsible for global climate change, are more vulnerable to and suffer more from the negative impacts of climate change and do not have the funds to take climate change adaptation measures. In contrast, developed countries, with their financial resources and technology capacity, are in a better position for taking immediate actions to reduce their GHG emissions. The UNFCCC recognized the abnormal burden of climate change to developing countries and established the principle of 'common but differentiated responsibilities': developed countries are obliged to take the lead in responding to climate change and support the climate change actions via technology and fund transfer.

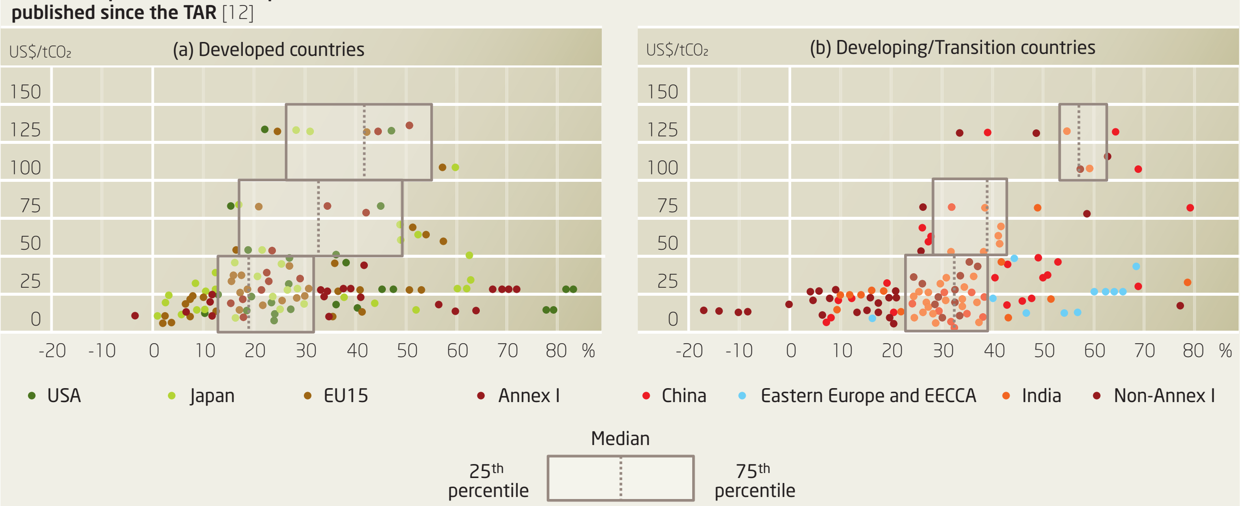
The Kyoto Protocol established specific emission reduction targets for developed countries and economies in transition and created the 'Clean Development Mechanism' so that additional emission reductions in developing countries could get carbon funding through selling their credits to developed countries. Since the first CDM project was registered in November 2004, CDM has effectively injected tens of billions of US dollars of investment in developing countries. The 3788 CDM projects already in the UNFCCC CDM pipeline at the end of July 2008 are expected to generate over 2,700 MtCO_2 of emission reductions by the end of 2012 (Figure 22). New projects are continuing to enter the international pipeline at a speed of around 150 projects per month.

92% of the expected CER generation as of 2012 are from 4 large developing countries, China, India, South Korea, and Brazil, indicating the existence of large low-cost emission reduction opportunities in these large and rapidly developing countries [11]. The CDM has proved itself an effective market instrument to channel funds toward emission reduction in rapidly developing countries.

As the first commitment period will end in 2012, the future of CDM and future international climate cooperation depends on the post-2012 climate negotiations. Technology and fund transfer remains the key issue of debate between developed and developing countries. How to enable a larger participation of developing countries in the global efforts against climate change through carbon finance, special donor financing, or in the form of great liberalisation of some key technologies is not agreed upon yet.

Figure 21

Relationship between carbon prices and CO_2 reduction from baseline in 2050 in selected counties taken from the literature published since the TAR [12]

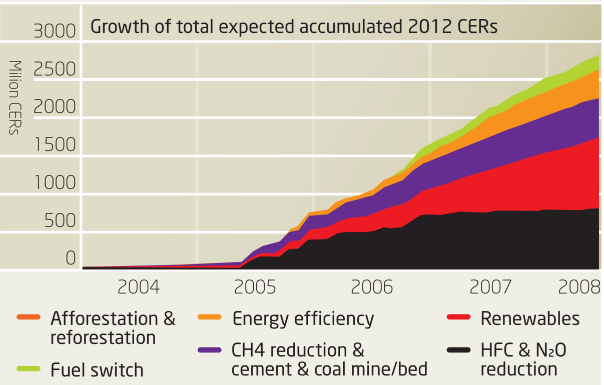


Note: The boxes show the range between the 25th and 75th percentile of the scenarios for each range. EECCA= Countries of Eastern Europe, the Caucasus and Central Asia.

7.2.4 Conclusions

Rapidly developing countries like China and India together with other large and fast emerging economies are important forces in shaping the world trends of development, energy, and climate performance in coming decades. These countries, due to their enormous new investments in energy infrastructure in the coming years, have the rare opportunity of transition toward low carbon development and low-cost GHG emission reduction.

Figure 22
Growth of total expected CERs from existing CDM projects [11]



China's and India's remarkable and robust economic growth over the last two or three decades has led many people to believe that both countries will continue to grow rapidly in the decades to come and such economic growth will pose enormous challenges in satisfying energy demand and mitigating greenhouse gas emissions.

With their vast territories and great differences in regional circumstances, China, India, and other rapidly developing countries will need to use almost every technological solution available to meet energy and climate challenges. A few technologies, however, are especially important. For electricity generation, the most important technologies for China and India will be those relating to clean coal, followed by nuclear power, hydro, wind, and solar. For the transport sector, public transport and clean vehicle technologies will be critical. Various energy efficiency technologies are also important to slow down energy demand increase and provide low-cost GHG emission reductions. China and India are already taking measures to address the economic, social, and environment challenges caused by their rapid increase in energy consumption and GHG emissions. This includes ambitious targets for renewable energy and energy efficiency, increased domestic production, and international technology and cooperation.

7.3 Africa

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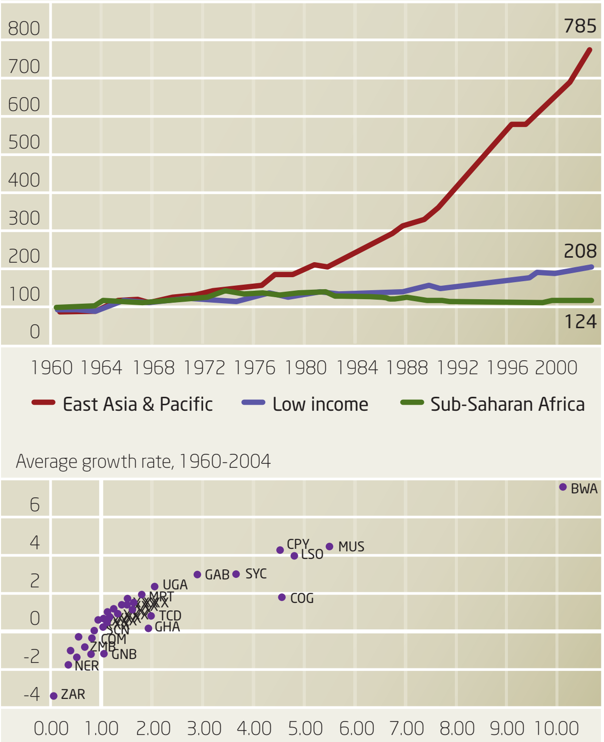
Figure 23

Per-capita income in 2004 relative to 1960 [1]

GDP per capita, 1960=100



Ratio of per capita income in 2004 to per capita en 1960

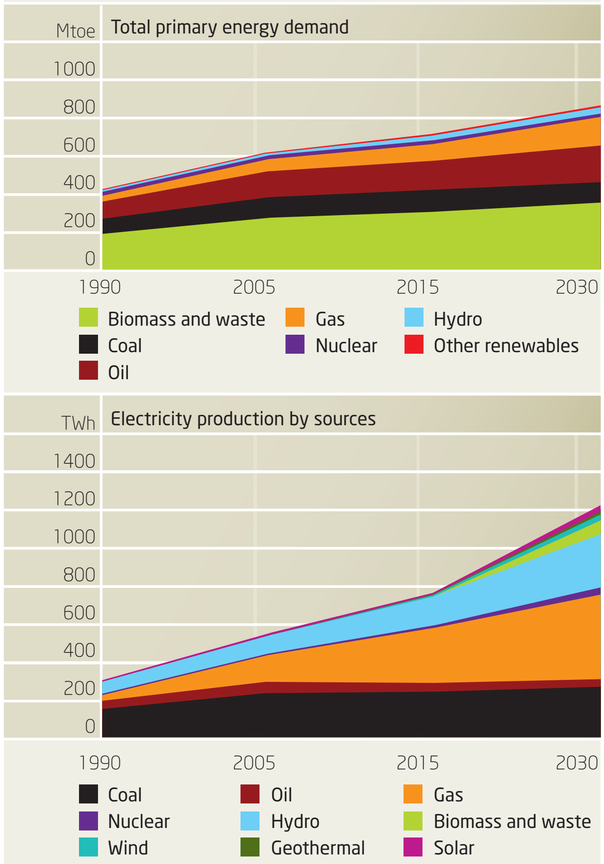
Compared to other regions of the world, economic development in sub-Saharan Africa (SSA) has been extremely slow during the last 45 years (Figure 23). Most SSA countries fall into the category of least developed countries (LDCs), and over this period a number of them have experienced negative average growth rates, while very few have been able to double their per-capita income. This is not the right place for a thorough discussion of this severe development problem, but it is clear that the energy future for these countries will depend very much on their economic development, which – seen in this historical context – may be difficult to predict. At the same time, economic development depends to a large extent on the abilities of LDC governments to put in place a physical, financial and organisational infrastructure, including an energy infrastructure, to serve as an enabling environment.

None of the existing long-term energy scenarios provides a disaggregated figure for the energy consumption of SSA or even of Africa as a whole[8]. Reasons for this may include the uncertainty of such estimates, and Africa's small share of global energy consumption. The energy demand projections in Figure 24 are therefore based on the alternative policy scenario from IEA's World Energy Outlook 2007, which

Figure 24

Total primary energy demand in Africa, and electricity production from various energy sources

World Energy Outlook alternative policy scenario [2]



[8] Existing energy scenarios to 2050, such as Energy Technology Perspectives from the OECD/IEA, the Energy Policy Scenarios to 2050 from World Energy Council and the Shell Energy Scenarios are all global scenarios, which do not provide disaggregated information on Africa [4, 5, 6].

[9] The Alternative Policy Scenario (APS) describes outcomes that would result from implementation of policies that are under consideration today. Many aspects of APS are comparable with the ACT scenario from the Energy Technology Perspectives [5]. The Blue Map scenario from Energy Technology Perspectives referred to in section 7.1 contains more optimistic assumptions, and includes development and widespread uptake of technologies, which are not available today. The global emission projections in 2050 for the Blue Map scenario and the ACT scenario are 14 and 27 Gt CO_2 annually, which should be compared to the baseline scenario of 62 Gt CO_2 [5].

forecasts total energy demand and electricity production up to 2030 [2][9]. The projections are based on an average economic growth rate of 3.9% per capita, which is well above the historical growth rates for the region as illustrated in figure 21. In spite of the low energy demand level in 2005, demand is only expected to increase with an average of 1.4 % per annum, compared to the world average of 1.3 %, and consequently Africa's share of global energy demand only increases from 5.3 to 5.9 % from 2005 to 2030. The energy demand in 2030 corresponds to an energy-related CO_2 emissions of 0.8 tonne per capita, compared to 16.5 t in the USA and 6.1 t in Europe [2].

Reducing CO_2 emissions should therefore not be the main concern in the development of an energy system for the poor people in Africa. Actors such as the World Bank, the African Development Bank and several bilateral donor organisations have therefore increasingly acknowledged that African LDCs should focus on economic development, transfer of least-cost technologies and adaptation to climate change, rather than on CO_2 reductions [3]. This focus is reflected in the following subsections.

7.3.1 Biomass for cooking

According to the projections illustrated in Figure 24, traditional biomass (mainly fuel wood) will continue to be a major energy source for cooking in SSA, especially for the majority of the population who live in rural areas, while for various reasons biogas is not expected to play a major role for household applications [2]. Although the fuel-wood crisis in SSA seems to have been exaggerated (Section 6.3.2), and despite forestry management programmes and improved wood-stoves, fuel wood is expected to remain a scarce resource around large towns in many parts of SSA [7].

7.3.2 Electrification: a big challenge

Current electrification rates in African LDCs are extremely low, at around 26% for SSA as a whole, and increased access to modern energy services is a major development goal [8]. Regional bodies such as FEMA, ECOWAS, EAC and CEMAC have set optimistic political goals of high electrification rates by 2015 [9], but these statements may be political wishes rather than realistic plans based on future investment flows. The World Bank draws a more pessimistic picture, believing that reaching 48% electrification in SSA by 2030 will require an annual investment of 4 billion USD, or twice the historical investment in the energy sector in SSA [3]. For 2050, a realistic estimate could be that about 80% of the population in SSA has access to electricity[10].

7.3.3 Regional cooperation to exploit diversity

While rural electrification is important for social and economic development, it will not greatly affect gross electricity demand: even once they are connected, rural dwellers are not expected to be able to afford large amounts of electricity. On the other hand, electricity consumption is expected to increase significantly in urban areas, where people are striving for modern lifestyles copied from the North.

To meet this increasing demand for electricity, it will be essential to exploit Africa's diversity of energy resources. Oil and gas reserves are concentrated in Northern and Western Africa. Hydroelectric, geothermal and, increasingly, natural gas potential exist in Central and Eastern Africa, while Southern Africa has coal and some natural gas.

At present there are embryonic attempts at regional integration between North, West, East, Central and Southern Africa, via a transport infrastructure for gas, oil and especially electricity [10, 11]. By 2050 the regional power pools are expected to be interconnected to form an Africa-wide power pool that will also link to Europe and the Middle East. The process will start with interconnections between the strongest African economies, which at the same time will benefit poorer countries in between [11].

The driver for this interconnection will be the regional spread of energy resources in SSA. Cheap coal from South Africa, natural gas from Nigeria, and hydropower from Inga Falls in the Democratic Republic of Congo are examples of resource concentrations that cannot be exploited efficiently by individual countries. The hydro potential at the fully-developed Inga Falls facility, for instance, is estimated to be 39 GW, or 288 TWh/y, which is enough to supply 23% of Africa's predicted electricity demand in 2030 [12].

7.3.4 Hybrid and non-grid systems

Large-scale infrastructure investments need to go hand in hand with the development of decentralised energy systems at the community level. The first of these are expected to be based on small diesel generators, but from 2010 to 2020

[10] The WEC [12] estimates that the current 2 billion people without access to electricity will have fallen to about 500 million by 2050.

they will increasingly take the form of hybrid systems based on small-scale hydro, wind or PV. The diesel component of these hybrid systems may increasingly be replaced by biofuels, as long as this does not conflict with food production.

Most LDCs in SSA have rather low population densities, and in a number of countries people live in dispersed settlements rather than nucleated villages. This means that non grid-based rural electrification will be the least-cost option for a fair part of the population. As an example, a recent energy plan for Burkina Faso projects that 38% of villages, corresponding to 8% of the population, will not be covered by either grids or mini-grids before at least 2020, because they are simply too far from the existing grid, too small and too dispersed [13]. In addition to this 8% of the population, a large number of people living in dispersed areas around nucleated settlements are likely to be served in the cheapest way by solar home systems (SHSs) [14]. This example indicates that SHSs may play an important role for rural electrification in Africa as a supplement to grid based systems.

7.3.5 Transport

Transport demand is expected to increase significantly in SSA until 2050, although at a lower rate than in the North due to the low economic capacity of a large part of the population. Locally-produced biofuels may be an option for cheaper transport fuel in some countries with low population densities, but in general the transport sector is likely to follow the technological development path for both individual and public transport in the North. This will include electrically-powered public transport in large cities, and a large share of gasoline and diesel cars replaced by electric or hybrid vehicles before 2050. This is, however, expected to take place more slowly than in the North, assuming that OECD countries continue to export used cars to Africa.

7.3.6 Conclusions

Compared to other regions, the rate of economic development in SSA has been extremely low, and in some cases even negative, over the last 45 years. Future energy development in LDCs will depend strongly on economic growth, which – seen in a historical context – is difficult to predict. At the same time, establishing an enabling environment in terms of energy infrastructure may be crucial to social and economic development. Projections to 2030 show that reducing CO_2 emissions will not be the main concern when developing an energy system for Africa's poor. Development actors have therefore increasingly acknowledged that in African LDCs the focus should rather be on economic development, transfer of least-cost technologies, and adapting to climate change. Nevertheless, through carbon financing there is likely to be an increased opportunity for the application of climate friendly energy technologies.

Projections based on such assumptions indicate that biomass will still be important for cooking in 2050. The present low electrification rate of 26% may, under optimistic conditions, increase to about 80% by 2050. Increased cooperation between existing regional power pools will be essential for exploiting large but regionally diverse resources, such as hydro, coal and natural gas, in providing electricity to meet increasing urban demand.

Rural electrification will to some extent depend on affordable grid-based electricity from hydro and coal, but many dispersed settlements are expected to be supplied mainly by individual PV systems or mini-grids based on hybrid PV and diesel or biofuel. According to projections, transport will increase significantly, but at a slower pace than in the North. Gasoline and diesel cars are also likely to be replaced by electric and hybrid cars more slowly than in the North.

CO_2 reduction strategies up to 2020

8.1 Danish CO_2 reduction scenarios

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Based on a review of recent low-carbon energy system studies for Denmark, this section discusses the most important options for significantly reducing Danish CO_2 emissions within the next 10-50 years. We begin with an overview of the present Danish energy system, focusing on the availability of renewable energy resources. After this comes the main conclusions of six different energy system studies for Denmark, which are used as input to a discussion about CO_2 emission reduction, and finally a conclusion.

8.1.1 The present Danish energy system

Denmark has excellent wind resources, thanks to its flat terrain and nearness to the sea. Climate and hydrology allow high yields of biomass from agriculture, although land itself is a scarce resource due to the country's small size and relatively high population density. The long Danish coastline could allow wave energy to become important in the future. Photovoltaics and solar heating could also contribute in the longer term, though their cost-effectiveness are not as attractive as in sunnier countries to the south.

Denmark's power system is presently characterised by combined heat and power (CHP) plants delivering heat to district heating systems, and a high proportion of wind power. The CHP plants are a combination of a few large plants fuelled mainly by coal and natural gas, and a large number of distributed CHP plants using natural gas, straw and municipal waste.

Fuel for road transport is dominated by gasoline and diesel.

Gross energy consumption in Denmark increased by only 5% during the period 1970-2006. This was because of the introduction of CHP plants and wind power on the supply side, and energy efficiency improvements on the demand side (energy savings) [1]. CHP plants improve the system efficiency while the influence of wind power is described through statistical methods. In statistics for gross energy consumption wind power is counted as PJ electricity produced while coal used in a power plant is counted for by its caloric value (energy content using lower heating value) – therefore a replacement of thermal power by wind power will reduce the gross energy consumption in the statistics.

8.1.2 Low-carbon energy studies

Concerns over global warming and energy security have placed renewable energy and CO_2 emissions reduction high on the Danish political agenda. This has resulted in a number of energy system studies:

A Visionary Danish Energy Policy 2025 [Ministry for Transport and Energy 2007]: was launched by the Government in January 2007, focusing on the framework for a future energy policy. The main idea is that energy technologies should be chosen through a combination of market mechanisms and political regulation. The government wishes to secure a future energy supply that is safe and reliable, environmentally friendly, and supports growth and competitiveness. Goals to be reached before 2025 include at least 30% renewable energy, gross energy consumption at the same level as in 2006, and a 15% cut in fossil fuels compared to 2006. The long term vision is a total phase out of fossil fuels in Denmark [2].

IDA Energy Plan 2030 [IDA 2006]: The Danish Society of Engineers (IDA) proclaimed 2006 an "energy year", during which it examined future energy solutions for Denmark. As a framework, the IDA adopted three main targets for 2030: Denmark should be self-sufficient with energy, as it is today; greenhouse gas emissions should be half their 1990 level; and exports of energy technology should quadruple, with a doubling of jobs in the energy sector. IDA used a model of the energy system, known as EnergyPlan [3], to find the most cost-effective way to meet these targets [4].

Danish Greenhouse Gas Reduction Scenario for 2020 and 2050 [EA Energy Analyses and Risø DTU 2008]: was drawn up by EA Energy Analyses and Risø DTU for the Danish Environmental Protection Agency (DEPA) and the Danish Energy Authority (DEA) in 2007. It contains two scenarios for 2020 and three for 2050; they account for all the greenhouse gasses emitted in Denmark, with the exception of international air and ship traffic. The scenarios are analysed in a spreadsheet-based energy system model called STREAM (see description of model in the report). For 2020, the main goals were to reduce greenhouse gas emissions by 30% or 40% compared to 1990 and for 2050 the reduction goals was 60% to 80% [5].

Cutting CO_2 ***Emissions [Greenpeace 2008]***: describes the results of an analysis prepared for Greenpeace in January 2008, setting out what is needed to meet reduction targets for 2008-12 and 2020. The analysis is based on the SESAM model [6], which differs from the tools used in the other studies in that it allows investments and energy balances to be tracked year by year. The framework for the analysis was that CO_2 emissions in 2020 should be 40% below their 1990 level, and oil and natural gas consumption should decline [7].

Scenarios for Danish GHG Reductions in 2020 and 2050 [COWI 2008]: were prepared in 2007 by the consultancy COWI for the Danish Environmental Protection Agency (DEPA) and the Danish Energy Authority (DEA). The focus is on energy supply technologies, transport technologies, and GHG reduction measures outside the energy sector. The analysis yielded marginal abatement cost (MAC) curves, which rank measures according to their abatement costs, for 2020 and 2050. The marginal abatement cost is found by comparing each investment option to a baseline case and dividing its cost by the resulting CO_2 reduction [8].

The Future Danish Energy System [The Danish Board of Technology 2007][11]***:*** In 2004 the Danish Board of Technology invited the largest players in the energy sector, researchers, NGOs and the Danish Parliament to help investigate options for the development of the Danish energy system. Technology scenarios were developed to show how by 2025 Denmark could halve its CO_2 emissions compared to 1990, and halve its oil consumption compared to 2003. This study led to the development of the STREAM modelling tool. All stakeholders were involved in the process of creating the scenarios through workshops, meetings and hearings while findings were continuously disseminated in newsletters [9].

Table 18 summarises the main assumptions and conclusions of these studies, with emphasis on the years from 2020 to 2030. ***All the studies except A Visionary Danish Energy Policy achieve*** CO_2***/GHG reductions in the order of 40–50%, compared to 1990, by 2020-2030.*** Increases in investment and fuel costs compared to business-as-usual scenarios are either negative or below 0.5% of GDP, meaning that these low-carbon energy systems would cost society little. Most of the studies assume no decrease in economic activity; they envisage exponential growth in GDP and private consumption, in line with the official forecasts from the Danish Ministry of Finance. IDA Energy Plan and Cutting CO_2 Emissions both assume saturation in the demand for transport, while Cutting CO_2 Emissions generally assumes significantly lower growth in energy demand than the other studies.

The conclusion that large CO_2 reductions can be achieved within the next 12-22 years, with low additional costs while maintaining high economic activity, is very interesting. It contradicts real-world experience, i.e. the fact that Denmark will probably not be able to fulfil its CO_2 emissions reduction targets for the first Kyoto period (2008–2012) through domestic reductions alone [10].

The predicted costs of reducing GHG emissions rely on many assumptions, including future fossil fuel prices; high fossil fuel prices make the scenarios based on high proportions of renewable energy more attractive. Interestingly, the oil prices assumed in five of the studies are significantly lower than present oil prices.

Furthermore, this type of analysis is limited in its coverage of macro-economic effects such as market disturbances, rebound effects, labour effects and changes in tax revenues. Except for Scenarios for Danish GHG Reductions in 2020 and 2050, by COWI, the studies exclude externalities such as socio-economic costs related to health effects, environmental impacts and damage to buildings and monuments.

The modelling tools used in the presented type of scenario analyses describe technically possible and economically feasible solutions' for future energy systems. They do not include political processes and related transaction costs linked to the approving of new policy, legislation and regulation, e.g. setting energy efficiency targets and standards. Market failures; such as a private investor's short term investment horizon sometimes leading to in-optimal solutions for the society – is not treated in this type of scenarios. The scenario analysis simply assumes that the "right" political decisions are made in adequate time and that private investors do what is best for the society. Therefore, the scenarios should be seen as guidelines to how our society technically can reach certain environmental goals at a certain socio-economic cost. They are not telling us how to regulate the markets and which political decisions we have to take when. That is the next step in the process and therefore the involvement of politicians and other decision makers is very important.

Figure 25 compares predictions of gross energy consumption from the different studies (note that the target years also differ). Compared to A Visionary Danish Energy Policy, all the other studies assume significant energy savings, resulting in lower total energy consumption and reduced use of coal, natural gas and oil. Reduced dependence on fossil fuels will to some extent counteract the decrease in Danish oil and natural gas production expected in the coming years. Production is expected to fall close to zero before 2050 (Statement on the North Sea to the Parliament by the Minister for Economic and Business Affairs, from 2003). However, fossil fuels will

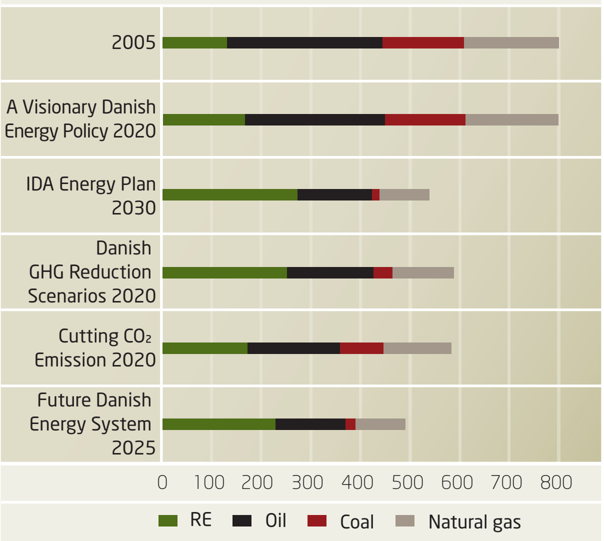
[11] The Danish Board of Technology is an independent body established by the Danish Parliament. The Board is advising the Danish Parliament and other governmental bodies in matters pertaining to technology.

Table 18
Main conclusions of, and assumptions behind, six Danish energy system scenario studies

Title of study	A Visionary Danish Energy Policy 2025	IDA Energy Plan	Danish GHG Reduction Scenarios	Cutting CO^2 Emissions	Scenarios for Danish GHG Reduction	The Future Danish Energy System
Commissioned for	Danish Government	IDA	DEPA/DEA	Greenpeace	DEPA/DEA	Danish Board of Technology
Prepared by	DEA	Aalborg University	EA Energy Analyses, Risø DTU	ECO Consult	Cowi A/S	EA Energy Analyses, Risø DTU, DONG Energy, Energinet.dk
Published	Jan 2007	Dec 2006	Feb 2008	Jan 2008	Feb 2008	Apr 2007
Time perspective	2025	2030	2020, 2050	2020, 2030	2020	2025
GHG/CO_2 reduction compared to 1990	GHG: –15%	CO_2: –60%	GHG: –40%, -80%	CO_2: –40%, –50%	GHG: -50%	CO_2: –50%
Renewable share (%/net)	30%	44%	30%, 100%	30%, 45%	N.A.	46%
Savings (%/year)	1.25–1.5%	1.8%	1.9%	1.5-2%	N.A.	2.8%
Oil price (USD/barrel)	50	68	57, 75	123, 140	50	50
CO_2 quota price (€/ton)	24	20	24	N.A.	40	20
Growth parameters (GDP, private consumption, demand for transport)	Exponential (2.)	Exponential (saturation in transport)	Exponential (1.)	Saturation	Exponential (1.)	Exponential (2.)
Interest rate (%)	6%	6%	6%	5%	6%	6%
Cost (% of GDP)	?	< 0%	0.1%, 0.5%	< 0%	0.5%	~ 0%

Comment (1.) Economic growth projections from The Danish Energy Authority, Jan 2008
Comment (2.) Economic growth projections from The Danish Energy Authority, Jan 2007

Figure 25
Gross energy consumption (PJ/year)



Gross energy consumption by fuel category. The dominant renewable energy sources are wind and biomass. The results presented in this graph does not include energy consumed in the North Sea (oil and gas exploration). There are differences between the studies in the way they treat international air transport.

retain a significant role, providing 40–50% of Denmark's energy until at least 2030. The proportion of renewable energy increases over the years, so the studies with later target years have generally higher shares of renewable energy.

The most important measures for achieving these very positive results are:

Energy savings: Yearly reductions of the order of 1–3% in energy consumption, compared to a development with energy efficiencies fixed at present levels. Energy-saving measures often have attractive payback times; the IDA Energy Plan, for instance, concludes that energy saving is the cheapest way to ensure security of supply and reduce CO_2 emissions. This can be difficult in practice, however, because it involves influencing the choices of very large numbers of energy consumers.

More efficient conventional vehicles, and plug-in hybrid vehicles: Curbing growth in the energy consumption of road vehicles is crucial to achieving CO_2 emission reduction targets, as the transport sector at present is nearly 100% reliant on fossil fuels. Using renewably-generated electricity as the fuel for plug-in hybrid electric vehicles also helps to introduce renewable energy to this sector. Toyota has announced that a plug-in version of its Prius hybrid car will be on the market in 2010, so it could be feasible for plug-ins to form a significant share of the Danish car fleet by 2020–2030. Plug-in hybrid vehicles will also help electric companies handle the variability and limited predictability of wind power in a cost-effective way.

Wind power: Denmark already has significant experience with wind power, as well as good wind resources, so increasing the share of wind power is an obvious move; most future expansion is likely to be offshore. One problem is the need to reinforce the power transmission grid, in part to meet the needs of future offshore wind power plants. Planning permission for new overhead lines is hard to obtain, due to opposition from local communities. Underground and undersea cabling are alternatives, but are likely to cost more.

Biomass: Used to heat buildings, to supply process heat for industry, and in CHP plants. Denmark already has a large body of knowledge about the use of straw and wood pellets for CHP, making this technology attractive. The development of second-generation biofuel technologies could make biofuels a sensible choice for transport in the future.

Flexibility: Handling large amounts of wind power, which is fluctuating in nature, requires flexibility in both power consumption and in other generating technologies. There are many ways to do this, including heat pumps, flexible pricing mechanisms and appliances, and the use of electricity for transport (see above).

Infrastructure planning: Decisions such as where to build new transmission lines, where to upgrade existing lines, whether to use overhead or underground cables, and where to locate new wind farms can also help to support greater use of intermittent power sources such as wind. These are political decisions that create the framework within which the energy markets function, and they need government involvement.

Energy markets: These are important in optimising the use of fuels and infrastructure, and to drive investment in new technology. New and improved market measures are needed to internalise costs connected with energy conversion and use that are currently treated as externalities. To take advantage of potential demand flexibility, future markets will need to be able to distribute price signals to end-users.

8.1.3 Conclusions

Significant CO_2 emission cuts by 2020 to 2050 will require a mix of new measures covering both energy demand and energy supply. The costs are low compared to continuing with an energy system dominated by fossil fuels. The most important measures will be energy savings (including the transport sector), plug-in hybrid electric vehicles, wind power and biomass.

The scenarios presented here show that it is possible to make ambitious CO_2 cuts without compromising economic growth. This is a complex issue, however, involving politicians, energy companies, industrial energy users, scientists, educational institutions and the energy-using public. We all need to understand the role each of these actors play in creating our future energy system.

An important tool here is the scenario process, for instance as set out in the project The Future Danish Energy System, facilitated by the Danish Board of Technology. Open debate on scenarios that involve all the stakeholders gives a holistic view of the energy system, not least to the politicians, and helps to locate planning bottlenecks and market imperfections.

Scenarios and roadmaps created through open processes and involving both politicians and the public can combine complex analysis of energy markets and systems with the political decisions needed to ensure that Denmark meets its environmental goals and secures its future energy supplies.

8.2 Global CO_2 reduction strategies up to 2020

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8.2.1 Introduction

A global CO_2, or more precisely green house gas reduction strategy must work towards stabilizing the concentration of greenhouse gases in the atmosphere because higher concentrations are going to increase the rate of global warming [1]. In this sense it differs from country level strategies which are mainly focused on stabilizing the greenhouse gas emissions at certain agreed levels. This difference arises due to the inherent property of the greenhouse gases that they affect the atmosphere for many years after they have been emitted [2]. The country level strategies are a result of negotiations at the global level where global strategies set the boundary within which the negotiations are conducted.

The IPCC Fourth Assessment Report [3] assesses technological mixes for different CO_2 stabilisation scenarios up to 2100. In this section we have a more modest agenda: to bring out more explicitly the technological options that would be needed in the short term (before 2020) to stabilise atmospheric GHGs at around 450 ppm CO_2e. To do this we looked at the background literature for the IPCC Fourth Assessment Report [3] and the IPCC Scenario Database for the Special Report on Emission Scenarios (SRES) [4].

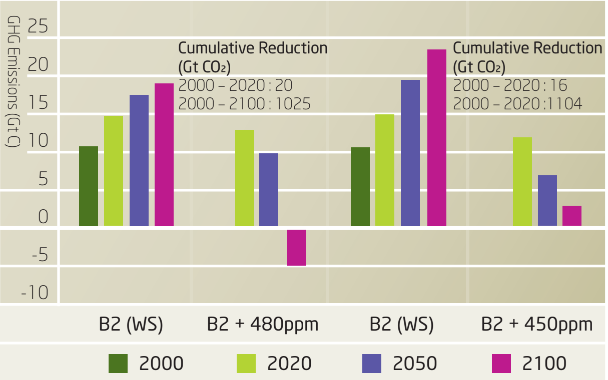
CO_2 reduction strategies may not necessarily be costlier compared to a strategy with no explicit policies to mitigate CO_2. In a detailed review of CO_2 mitigation scenarios it was found that the optimal costs for many low and high CO_2 scenarios were identical [5]. There is, however, a path dependency, and to achieve low CO_2 emission in the long term it is important to latch on a low-emission technology mix early [6].

8.2.2 Global GHG emissions

The SRES classified its scenarios into four storylines designated A1, A2, B1 and B2 [7]. These storylines have become a standard starting point for modellers working on climate change issues across the world. Of the four, we found that the B2 storyline has been used most commonly when comparing the various stabilisation scenarios [8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. The B2 storyline describes a world in which “the emphasis is on local solutions to economic, social, and environmental sustainability” [7]. In view of this, we chose

Figure 26

GHG emissions for the B2 storyline and the corresponding low-carbon stabilisation scenario



B2 (WS) – B2 Storyline within stabilization
B2 + 480 ppm – B2 Storyline within stabilization at 480 ppm CO_2-e
B2 + 450 ppm – B2 Storyline within stabilization at 450 ppm CO_2-e

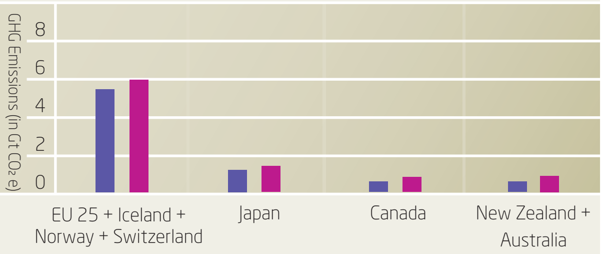
Sources [13, 16]

scenarios based around the B2 storyline. In the scenarios following the B2 storyline the general trend is of increasing emissions up to 2100 (Figure 26) [3] which would mean increasing concentrations of CO_2 in the atmosphere. Increasing concentrations mean increasing temperatures and higher risks [3]. If we want to limit the risks then it is important to keep the CO_2 concentrations at the lowest feasible target which is 450 ppm CO_2e. However there are very few scenarios which have looked at stabilization at levels below 500 ppm CO_2 because 450 ppmv is considered as a difficult target and almost out of reach [18].

However we still stick to a 450 ppmv CO_2e stabilisation regime, because past experience shows that achievement has been below what has been agreed upon. Most Annex I countries which took binding commitments for reducing their GHG emissions will not be able to meet their commitments (Figure 27). If there is agreement on a stiff target (say 450 ppmv CO_2e) then the chances are that the actual figure will be higher (say 500 ppmv CO_2e).

The 450 ppm CO_2e stabilization target would mean emissions should start reducing after ten years from now [3] and given the technological lock the emission path in stabilization regime is not much different from the B2 scenario without stabilization targets. Therefore, the cumulative GHG reductions achieved before 2020 are very small (Figure 26). The stabilization paths vary between scenarios, however, early action gives more flexibility in the future. In Figure 26 the scenario with lower emissions in 2020 and 2050 is able to sustain positive GHG emissions even in 2100. However, early action would require rapid deployment of technologies which are currently close to commercialisation.

Figure 27
Annual GHG emissions for Kyoto Annex I countries [19]



Russia and Ukraine are not included, since both countries underwent major economic restructuring

8.2.3 GHG mitigation potentials

GHG emissions can be reduced through action in the energy, industrial, agricultural, forest and waste sectors [3, 17]. The energy sector currently accounts for the largest share of GHG emissions (Table 20), and this share will rise in the future [3]. Table 20 also shows that in 2000 a substantial fraction of total emissions was from gases other than CO_2, though this share is projected to decrease [3].

The IPCC Fourth Assessment Report [1] does not provide us with specific technologies, but it does show details of the GHG mitigation that would happen across different sectors (Figure 28). We will use this information to make some assumptions about technologies.

We have focused on the 450 ppm stabilisation scenario, which will require strong GHG mitigation and therefore a high permit price. At a high permit price we find that the top four sectors which would contribute the most to GHG mitigation are energy supply, industry, transport, and building (Table 19).

Table 19
Mitigation to be expected from the industry sectors with the largest reductions, assuming a permit price of USD 100/tCO_2e

Sector	Mitigation Potential (GT CO_2-eq.)
Energy Supply	~ 12
Industry	~ 4
Transport	~ 1.5
Building	~ 1.5
Agriculture	~ 1.2

8.2.4 Mitigation technologies

New technologies that can reduce GHG emissions arise from the interaction of three drivers: research and development, learning-by-doing, and spillovers which happen due to technological developments in other areas [6]. Policies specifically related to climate change affect mainly the first two of these, first by increasing R&D on technologies with important potential for GHG mitigation, and second by creating incentives for their deployment, leading to faster learning-by-doing. GHG problems cannot be solved by a single technology [2] and therefore R&D investments would have to be distributed over a wide portfolio of technologies.

Energy conservation and efficiency

For stabilisation at 450 ppmv CO_2e, energy efficiency improvements are important in the period up to 2020, and in the longer term they become the largest single source of mitigation (Figure 29). Many short-term energy efficiency measures even have negative abatement costs [20]. The barriers to energy conservation are therefore mainly institutional and would require changes in policies to pass on correct signals to consumers.

Efficiency improvement and energy conservation are the dominant choices in the industrial and building sectors.

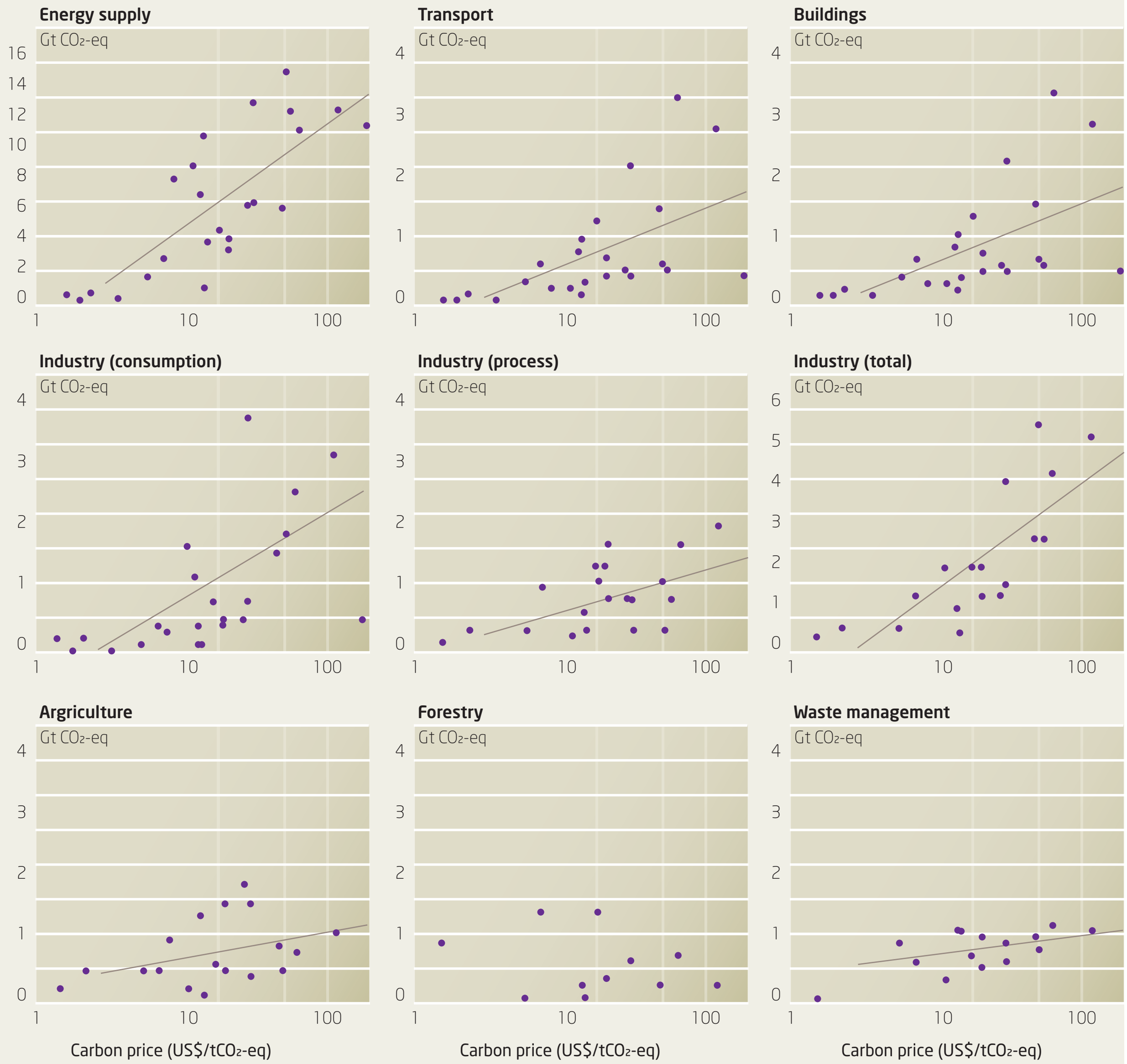
Industry

Industry uses energy, often in the form of steam, as a source of process heat and to drive machinery. R&D should focus on redesigning processes so that they require less steam, heat or mechanical energy to operate [2]. Improving the efficiency of individual equipment items such as boilers and electric motors is often difficult, since in general these are already highly efficient [2], but this does not mean that such generic improvements should be ignored.

Table 20
GHG emissions by gas and by industry, 2000 (Mt CO_2e/y) [17]

Industry sector	Gas				Industry total	Industry share (%)
	CO_2	CH_4	N_2O	F		
Energy	23,409	1,467	224	0	25,100	67
LUCF & Agriculture	3,435	3,109	2,999	0	9,543	25
Industry	829	0	158	447	1,434	4
Waste	0	1,357	92	0	1,449	4
Gas total	27,673	5,933	3,473	447	37,526	100
Gas share (%)	74	16	9	1	100	

Figure 28
Permit price versus emission reduction level for several sectors, 2030; adapted from IPCC Fourth Assessment Report [3]



Building sector

The building sector offers tremendous opportunities for energy conservation, but making good use of these involves giving suitable incentives to end users. Building codes, energy labelling and regulatory innovations all have a part to play. In the longer term, efficiency can also be improved through a shift in technological paradigm. In lighting, for example, we will move from incandescent bulbs to fluorescent lamps, and then to solid-state (LED) lamps [2].

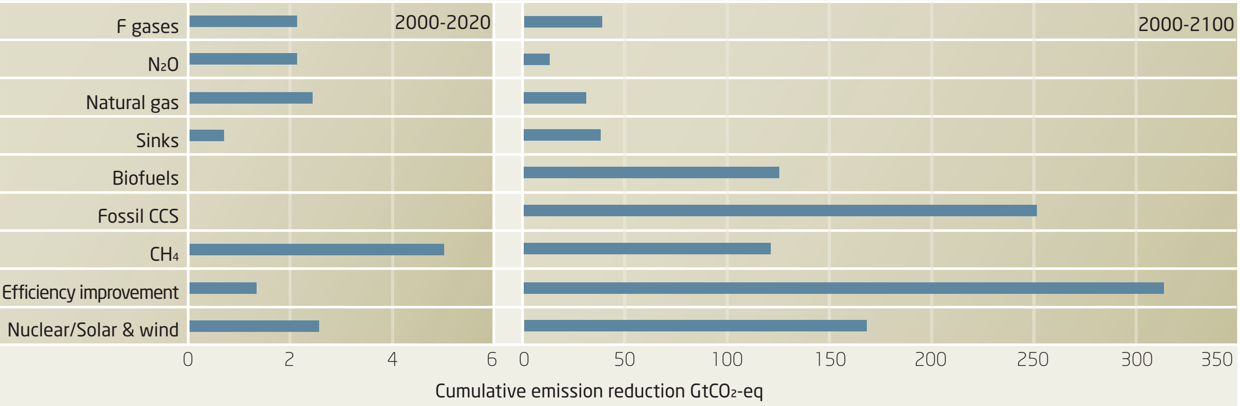
Carbon capture and storage

Carbon capture and storage (CCS) could be an important long-term mitigation measure in strong stabilisation regimes [3], but we see none coming up commercially until 2020 (Figure 29). CCS offers the flexibility of continuing to use the fossil fuels on which we have become so dependent.

CCS can be used in combination with coal, oil, gas and biomass. Coal-fired power plants are not the cheapest option for CCS, but they have the largest potential for GHG mitigation [2]. The required CO_2 removal technology was discussed in the last issue of this Energy Report, but it is also important to understand the consequences of storing large quantities of CO_2 underground.

Figure 29

Mitigation choices for stabilisation at 450 ppmv CO_2e [16]



Renewables

Renewable energy will play a major role in the strong stabilisation scenarios [3]. Renewable technologies help to reduce the costs of mitigation through the sharp reduction in technology costs that follow from large-scale deployment [2]. For instance, large-scale use of solar PV in the quest to meet a stabilisation target of 450 ppmv CO_2e would reduce the costs of this technology. There is a wide range of renewable technologies, and a diverse portfolio may help to reduce the risks [2].

A substantial part of the world's electricity, especially in the two largest developing countries, India and China, is generated from coal. There is strong pressure to continue this coal dependence, even in a future in which these two countries will need to contribute more to reducing GHG emissions. For stronger mitigation, a major shift is required away from coal towards less carbon-intensive fuels like natural gas and renewables.

Among the renewable sources, solar and wind are the most widely implemented, although continued R&D is required to further reduce their capital costs. Solar and wind face problems in grid integration due to their intermittency. These issues require R&D in electricity storage and transmission technologies [2].

The years up to 2020 will see limited use of biofuels (Figure 29) beyond what would happen in the base scenario, since first-generation biofuels come into conflict with food security, and second-generation biofuels will take some time to be commercialised. In the longer term biofuels could play a major role in a carbon-constrained regime [16,2]. Biomass with CCS would shift a lot of biomass for electricity production, leaving little for biofuels because with CCS biomass would have negative emissions. The overall availability of biomass will always be constrained by the availability of land [2] which has to meet competing demands for food, pasture, forests and urban development.

Nuclear

In the strong stabilisation regimes, nuclear power could play an important role in the short as well as the long term [3]; stabilisation at 450 ppmv CO_2 e would be difficult without it. In the short term, the nuclear option requires the creation of sites for permanent disposal of nuclear waste. In the longer term nuclear waste would be a major problem, so it would be essential to design reactors than can recycle used fuels [2].

Non-CO_2 gases

The largest contributor in this category in the long term is methane [3] though in the shorter term N_2O and F gases (i.e., HFC, PFC and SF_6) taken together, will be equally important. There are two ways to reduce the effect of non-CO_2 emissions: first by reducing the formation of these gases, and second by capturing and re-using them. Of the two, capture and re-use has lower marginal abatement costs [2]. Methane emissions can be reduced very cheaply due to the value of methane as an energy source; two very successful examples are reduced flaring from oilfields and refineries, and the extraction of methane from coal mines.

Hydrogen

In the transport sector the two main technological solutions are biofuels and hydrogen. Hydrogen fuel systems can even be attractive when they do not offer major climate change benefits, thanks to their ability to reduce local air pollution [2]. Carbon penalties provide further advantages by encouraging the production of hydrogen from biomass, or from fossil fuels with CCS. For hydrogen transport systems to become commercially viable, however, R&D is required in hydrogen storage, distribution and use [2].

8.2.5 Conclusions

Climate change is a long-term problem, and early action is important in order to remain on a lower emission trajectory that will provide flexibility in the future. Technologies that are important for short-term mitigation are not necessarily sufficient in the long term. A diversified portfolio of choices is needed, and this will require R&D investment over long periods before we reach the ultimate objective.

The stabilisation of emissions at 450 ppm CO_2e would require measures that will contribute to a sustainable society, such as increased use of renewables, energy efficiency and energy conservation. These will need to be supplemented, however, by measures such as nuclear power and CCS, which make no apparent contribution to sustainability. They may even reduce sustainability, since research is required to reduce the problems associated with nuclear waste and CCS.

Solar and wind are the key renewable technology choices for electricity generation in the future especially for early mitigation as they are mature and ready for commercialization. The diffusion of these two technologies will depend on our ability to reduce their capital costs, and also to overcome the barriers that hinder their integration into existing electricity grids. The latter will require research in the related areas of electricity storage and transmission.

The use of biomass is constrained by the availability of land and the need for improvements in crop productivity. Biomass could be converted into biofuels to replace fossil fuels in the transport sector, or used to generate power, especially in combination with CCS.

The focus on non CO_2 gases can also help in early mitigation besides bringing down the overall costs for mitigation. Nuclear is another technology which can help in early mitigation.

Strong CO_2 mitigation would also require providing correct policy incentives so that negative cost measures like energy efficiency are taken up. This is essential so that CO_2 mitigation happens at lowest cost.

Finally GHG mitigation efforts may create second-order effects and externalities that are currently difficult to foresee. Therefore R&D efforts should also focus on the externalities that can result from different technologies. A wide portfolio of technologies can also help in mitigating the risks arising from these unforeseen externalities.

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